NATIONAL ENERGY AUTHORITY

DEPARTMENT OF NATURAL HEAT

GEOTHERMAL POWER STATION

Preliminary Project Report on Power Station with Regard to Development at Námafjall or Krafla.

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Summary and Conclusions.

This report presents a study of feasible ways of exploiting the geothermal resources of the Námafjall/Krafla areas for the production of electicity by means of 8-16 MW power plant.

There appear to be no technical barriers in the way of installing such a thermal power plant. As to geology both thermal areas are considered equally suitable, but in view of environmental pollution and the delicate surroundings of lake Mývatn the Krafla area is preferred. Recent experiments carried out in El Salvador with disposing of discharged waters underground, i.e. by reinjecting the thermal water under pressure into drillholes, at the outskirts of the thermal area, give promising results, the Námafjall area should therefore not be excluded at this stage on grounds of danger of pollution.

It should be mentioned that a transmission line from the Krafla area would be longer than one from the Námafjall area and the construction of an access road to a plant located there would also be necessary.

There are three main types of geothermal power plants to choose from, the difference primarily depending on the efficiency in utilizing the thermal energy, with higher efficiency requiring heavier equipment and higher installation cost.

With regard to efficiency in the utilization of the thermal energy a condensing turbine is chosen in favour of a back-pressure turbine, while the exploitation of drillhole water was not considered advisable as little experience has so far been gathered for that type of plants.

The intititial cost is estimated at 273 Mkr*, 311 Mkr and 365 Mkr and the annual operating cost 36 Mkr, 40 Mkr and 46 Mkr, as for 8 MW, 12 MW and 16 MW size power plants respectively. This corresponds to an initial cost of one KW at 34.000 kr. for 8 MW power plant 26.000 kr. for 12 MW plant and 23.000 kr. for a 16 MW size power plant.

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* Mkr = milliion Icelandic kronur.

Assuming an annual fully effective production time of 8000 hours the operating cost of a 8 MW power plant will be 0.60 kr./Kwh, that of a 12 MW power plant 0.44 kr./Kwh and that of a 16 MW power plant 0.38 kr./kwh.

From the above figures it can be inferred that the unit price of the electricity is in inverse relation to the size of the power plant, but the lowering in price is twice as great from 8 MW to 12 MW than from 12 MW to 16 MW.

Assuming full production a 55 MW geothermal power plant is considered the most economical size, but the present study does not include a power station of that size as a plant of that capacity would be comparatively large in this country.

As to the length of the time of construction it is assumed that an interval of 43 months would elaspe from the time a desicion is made to construct such a plant until it would be ready for production.

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Introduction.

The report presents the results of inverstigations and studies of the possibilities of electric power production by means of natural steam. In 1960 the consulting engineers of Merz and Mc Lellan in London made a feasibility study of the possibilities of power production from geothermal steam at Hveragerði. They reported negative results as the geothermal power station could not compete with the proposed Búrfell hydro-electric power plant, a main contributing factor being the rather low temperature in the wells in the Hveragerði area.

These conclusions led to a cessation of further studies for a while, but drillings in Nesjavellir and Námafjall in the years 1965 - 1966 revealed substantially higher base temperatures in drillholes, or 260-290^{o}C, which prompted renewed research.

In 1967 the engineering consultants Vermir s.f. prepared a report on electric power generation with back-pressure turbine at Námafjall, which eventually led to the counstruction of a 2.5 MW geothermal power plant at that locality. The station was equipped with a second hand turbo-generator bought from England, which had already been operationg for some years.

The staion was test operated in May 1969 and has been run almost continuously since then.

Expectedly there were various initial difficulties to cope with, the primary one being caused by precipitation of silicia from the steam into the safety valves of the machine, but this was overcome in a relatively simple way. In summer 1971 the turbine wheel was exchanged for a new one as originally planned, since the alloy in the shovels of the wheel were not considered suitable for natural steam. No corrosion nor erosion has so far been detected in the equipment of the station.

The procurement of steam took somewhat longer time than the installation of the station, as the Diatomite plant had to be supplied with additional steam simultaneously. In 1971 sufficient steam had been secured and from that time the station has operated at full output, at about 3 MW. The station has operated well and supervision is performed by daily inspection tours by the engineers of the Diatomite Plant.

During the first four months of 1972 the electricity output of the station was about 8 million Kwh.

This report comprises a project design of a geothermal power station working on the basis of steam condensation. It compares three sizes, 8 MW, 12 MW and 16 MW, with respect to the geothermal areas in Námafjall and Krafla. Both these localities are considered suitable, but local conditions are different. Locating a plant in the inhabited district at Námafjall would have certain advantages, whereas with regard to environmental protection the Krafla area would be preferable. The project report should be valid for other geothermal areas.

This report is prepared jointly by the Department of Natural Heat of the National Energy Authority and Verkfræðistofa Guðmundar and Kristjáns (Consulting Engineers) the main authors being K. Ragnars mechanical engineer at the National Energy Authority and J. Matthíasson mechanical engineer at the Consulting Engineers´office. Assisting collaborators and advisers were Prof. G. Björnsson and J. Indriðason, electrical engineer.

S. Thoroddsen and Partners (Consulting Engineers) made a preliminary plan for the power house and an acceas road to the Krafla area.

The chapter on the geology of the geothermal areas is written by K. Sæmundsson, geologist at the Department of Natural Heat of the National Energy Authority.

1. The thermal areas.

1.1 General geology of the Námafjall and Krafla areas.

All the high-temperature geothermal areas in Iceland are located within the active volanic zones and most are connected with central volcanoes, which, besides the high-temperature areas, are characterised by acidic volcanism, rapid build-up, and frequent small-scale volcanic eruptions and sometimes calderas.

The volcanic zone in Northern Iceland, west of the river Jökulsá á Fjöllum, is made up og several NNE-SSW striking fissure swarms. Near the middle of each swarm a central volcano occurs and within it a high-temperature area. The geothermal areas at Námafjall and at Krafla lie within the same fissure swarm and are thus geologically closely related, although their water systems are probably separate.

The Krafla area lies at an altitude of 500-600 m with peaks as high as 800 m. The Námafjall area lies at an altitude of 300-400 m. It is traversed by a low elongated ridge which extends from the Krafla area in the north to Ludent crater in the south. The hill Námafjall is a part of this ridge. Volcanic formations predominate in the landscape around Námafjall and the area has in fact become world famous for their great variety and beauty. As the Krafla area is rather remote, traffic has always been little there, it is therefore less known and can only be reached by tracks passable for 3 or 4 months during summer.

The surface in the Námafjall - Krafla area is to a large extent covered by lava flows of recent age, which poured from volcanic fissures during Postglacial Time. The lavas are composed of basalt with the exception of a few andesitic flows found north of Lúdent and Hlíðarfjall. Hyaloclastites and pillow lavas, the second main rock type forming the bedrock of the area, formed as a result of subglacial volcanic activity during glacial periods. This rock type forms elongated ridges which are situated directly above the feeding volcanic fissures (e.g. Námafjall and Dalfjall).

Apart from the hyaloclastites which are basaltic, acidic melt was also erupted during glacial periods. The acid rocks from steep domes (e.g. Hlíðarfjall and Jörundur), consisting of rhyolite, often perlitic due to rapid cooling on contact with glacial melt water. Lava flows were erupted in the Krafla area on to an icefree surface during the last interglacial.

The last major volcanic event during this period was the eruption of an ignimbrite layer still found to cover about 30 km^2 on the surface. Subsequently to this eruption a caldera about 8 km across collapsed in the Krafla area. The caldera has to a large extent been filled by subsequent hyaloclastites and lava flows. Hyaloclastites and basaltic periods are found in a few outcrops east of the caldera.

Faults and fissures in the Námafjall and Krafla areas are on one hand characterised by curved fractures lying almost concentric to the outlines of the caldera, some of which have fed lava flows and rhyolite domes. On the other hand there are dilation fractures and volcanic fissures following the general NNE-SSW strike of the fissure swarm. Subsidence and volcanic activity tend to increase towards the centre of the swarm, but post-glacial volcanic vents show a marked concentration in the Krafla caldera and at Námafjall. All geothermal activity and alteration due to natural heat in the Krafla area are found within the limits of the caldera. Active steam vents and hot ground are limited to an area of only 3 km^2 extending NNW-SSE between Leirhnúkur and Krafla. On the other hand extinct alteration extends over a much wider area totalling 35 km^2. Lukewarm ground water is found in a few places to the south of the main geothermal area.

An aeromagnetic survey has shown a magnetic low above the southern section of the caldera the shape of which coincides with surface manfestations of geothermal activity or alteration. The minimum values occurred where the thermal activity is most intense. This is believed to be caused by the decomposition of magnetite upon alteration in the thermal reservoir. Resistivity measurments have been used successfully to define the shape and size of the geothermal reservoir down to about 800 m depth.

At 150 m depth the reservoir does not extend far beyond the areas of steaming ground and most recent alteration. At 800 m depth it is much wider and includes all signs of altered ground in the SE part of the caldera.

Gravity and seismic surveys indicate a positive gravity anomaly and a rise in the seismic layer 2/3 interface below the caldera. We interpret this as evidence of high level intrusions, samples of which have been brought up as xenoliths in ignimbrite and pumice eruptions. The geothermal area at Námafjall is about 4 km^2 in size. Surface manifestations are more continuous and spectacular than in the Krafla area and cold, altered ground is found only within narraw limits outside the active thermal region.

The permable lava flows between Námafjall and lake Mývatn conduct heated ground water towards the lake, which issues in powerful springs at the lake edge between Reykjahlíð and Vogar. Geologically the Námafjall area is located about 4 km south of the Krafla caldera. It seems likely that a subsidiary center will develope there in the geolcgical future.

Resistivity and magnetic surveys define a thermal reservoir below Námafjall of a cylindrical shape coinciding with the distribution of surface manifestations. Thus, the Námafjall thermal area is clearly limited to a small tract within the main down-throw zone of the Námafjall - Krafla fracture swarm, leading to the conclusion that it is supplied by a local heat source (hot intrusions) at its base. In this case it should be regarded as unrelated to the Krafla thermal area.

Böðvarson has estimated by rough methods the energy output of several thermal areas wtih reference to heat loss through th surface. According to his estimate the natural heat loss of the Krafla area is a degree of magnitude less than that of the Námafjall area, or $5\text{-}25\times10^6$ Mcal/sec against $25\text{-}125\times10^6$ Mcal/sec. This estimate was made prior to detailed research. Our results indicate equally extensive thermal reservoirs in both areas, which rather contradict the suggestion of Krafla being much inferior. Steaming ground, mud pools and sulfur deposits are, however, more prominent at Námafjall.

The connection of the thermal activity with fractures and faults is conspicuous in both the Námafjall and Krafla areas. From descriptions of the "Mývatn fires", a volcanic episode lasting from 1724-1729, it is clear that extensive fracturing occurred in the Námafjall - Krafla fissure swarm all the way from Bláfjall in the south up to Gjástykki in the north. Where the new fissures and faults crossed the thermal areas new steam vents and solfataras resulted. This is mentioned for both Bjarnarflag and Leirhnúkur.

From the descriptions it can be deduced that steam explosion craters were actually generated at Leirhnúkur similar to what occurred accidentally during drilling at Námafjall a few years ago. Cool alteration patches commonly extend along faults towards the outskirts of the thermal areas. These patches probably originated in a similar way, when tectonic movements temporarily opened up channels for hot emanations outside the main steam aerea.

A characteristic feature of the Krafla area is a group of explosion craters all of which are located within the thermal area. The youngest of those craters is Víti which formed as the first phase of the "Mývatn Fires" in 1724. This eruption started as a volcanic explosion throwing out mixed basalt and rhyolite pumice and ended up as steam, throwing out mud and fragmented wall rock.

The mud and ash from the Víti eruption was carried south and forms a thick clayey deposit over much of the area where drilling is planned. The effect of such energy release from the geothermal reservoir probably caused a drastic temporal lowering in reservoir pressure.

Pure steam explosion craters are probably also to be found in the Krafla area and there is one known example of a crater wall with no intermixed scoria. The existing explosion craters indicate the existence of higly permeable aquifers below an impermeable surface layer. In case of ground fissuring or an eruption breaking out within the thermal area the pressure release may cause upflow of water, which can result in overheating in an environment of lowered pressure.

From the ratio CO_2/H_2 and the H_2 content in gases collected from steam vents and boreholes the temperature in the rock at about 600-1200 m depth can be estimated. This ratio indicates that maximum temperatures within the Námafjall area prevail below the eastern part of it with values as high as 275-305°C. The same kind of calculation for the Krafla area indicates highest temperatures of 245-285°C SE of the mountain Krafla.

It is of great importance to know, as far as possible, the behaviour and frequency of volcanic eruptions in the vicinity of sites of proposed engineering projects. We will therefore shortly discuss what geology has revealed as to the frequency of volcanic eruptions within both areas. Presumably the Námafjall-Krafla area had become deglaciated about 10.000 years ago. Since then 8 lava producing fissure eruptions have taken place in the Námafjall area and its vicinity, the most recent one being the "Mývatn Fires" of 1724-1729. This corresponds to one eruption every 1250 years. On the other hand the eruptions are not evently distributed through this period, rather they have occurred in two spells, the earlier of which had faded out about 8000 years ago. The second started only 2500 years ago and comprises four eruptions.

In the vicinity of Krafla there have benn 9 lava eruptions, all of them from fissures, since the end of the glaciations, two of which are common to the Námafjall area since the volcanic fissures extended through both. The division into spells of activity is not as clear as in the Námafjall area, yet three eruptions can be asserted to be younger than 3000 years. Besides the lava eruptions, explosion erutions have occurred within the thermal area at Krafla. The number of such eruptions is uncertain, but the major westward migrating episodes can be recognized, the last one being Víti. During "Mývatn Fires" only 250 years ago the main volcanic vents lay across the Krafla caldera. As this was a comparatively large eruption it is plausible to assume that the following few centuries will be quiet as far as volcanism is concerned.

1.2 Drillholes.

1.2.1 Drillholes in Námafjall. General review.

In the years 1947-1953 some shallow holes were drilled in the Námafjall area, mainly east of the mountain. Some of these holes emitted dry steam and although the temperature in the holes could not be measured at that time, they indicated high temperatures in the area.

The purpose of drilling these holes was to extract sulphur from the steam, but it soon became evident that sulphur could not become an economical product by itself. Therefore other ways of exploitation were sought whereby the thermal content of the steam could be utilized. This led to the idea of mining diatomaceous earth from Lake Mývatn and drying it by geothermal heat at Námafjall.

Two test holes were drilled for this purpose in the years 1963-1965. In spite of these holes being drill-technically a failure the first production well, well 3, was drilled in 1966. This well was in many respects unsuccessful both due to unsatisfactory drilling equipment and limited knowledge of the thermal area; its operation was abandoned in early 1969. At present 6 additional wells have been completed both for the Diatomite Plant and the electric power plant owned by Laxárvirkjun Power Company.

Wells 4 and 5 were drilled in summer 1968, wells 6 and 7 in the year 1969 and 8 and 9 in summer 1970. Considerable experience on the exploitation of geothermal energy has been gained through drilling and operating these wells, which is of great value for continued research in this field.

The finish of wells 6 to 9 is shown in Figs 1 - 4. In all cases a percussion drill has predrilled for the rotary drill. The percussion drillholes are about 30 m deep cased with 16" surface casing fixed by cementing. In one instance a 13 3/8" safety casing was used, i.e. in well 7, due to uncontrollable leakage at about 100 m depth. This casing is also fixed with cement. After these initial arrangements the wells are drilled 12 1/4" wide down to 200 - 250 m depth and cased to that depth by a 9 5/8" anchor casing.

The anchor casing is subjected to the greatest strain of the casings in the hole as in sustains the wellhead and is therefore subjected to greatest load in the hole. Successful cementing of anchor casing is crucial securing a continuous lining of concrete along the casing. Production casing is connected to the wellhead and extends down to 500 - 600 m depth. In two wells, 6 and 9, 6" liners have been used.

It must be admitted that the design and finish of the wells in the Námafjall area is not as good as is desireable, primarily due to the fact that the drilling equipment used (Norðurbor) is not powerful enough for wells of the dimension in case. Economical aspects may also be responsible to some degree.

The percussion drillhole is cased by a 16" surface casing secured with concrete, as it is not decided in advance whether to use a 13 3/8" safety casing, and it is not considered safe to drill to greater depth than about 100 m without fitting a safety valve on the well. A 13 3/8" safety casing is supposed to be put in when leakage and loss of circulation into the ground is so excessive, that sound cementing of 9 5/8" anchor casing cannot be garanteed. But in view of expenses the safety casing is only used when it is considered absolutely necessary.

The length of the anchor casing is 200 - 250 m althoug it would be desirable to let it extend somewhat further down, but this could not be accomplished as the drilling tools could not be relied on for cementing the casing to a greater depth satisfactorily. The importance of reliable cementing of casing will be discussed later. It would also have been preferable to put in a production casing, but this was out of the question with the available equipment.

In the case of soft ground with imminent danger of cave-in a 6" liner was supposed to be used attached to the lower end of the production casing. This liner was first put into well 9, as it was not considered necessary to use it in the other holes. There was no experience to rely on as to permissible softness of the ground, and after having been exploited for a year well 6 caved in.

It has now been redrilled and cased with a liner.

Figs 5 - 9 exhibit the division of the time of drilling between individual factors.

As the tables reveal the drilling is generally slower in the uppermost part of the well, as the securing of the hole by cementing off permeable layers, cementing for supporting the walls of the hole etc., consumes a great part of the time.

When some depth is reached, on the other hand, the drilling proceeds much more rapidly and the cost of drilling a hole would not increase greatly from drilling them deeper if proper drilling equipment were used. The tables also present a fairly good reference for the preparation of project plans and cost estimates for subsequent holes and a time schedule for completing them.

1.2.2 Loss of circulation, cementing and casing.

The most difficult aspects of drilling a hole are undoubtedly connected with cementing and securing good casing and finish. Loss of circulation is often very difficult to deal with, but must necessarily be repaired for the sake of safe drilling and casing.

Aquifers in the upper strata may cause intermixing of water whereby overheated water is capable of flowing from the lower part of a hole into veins higher up. Due to the boiling pressure of the superheated water this may lead to higher pressure in the hole than that caused by the water column, whereby the hole starts to erupt.

There are various methods for closing off a leakage depending on the nature of the leakage. The most common method is to pump cement into the opening thereby trying to check the leakage. Sometimes this is repeated several times, i.e. in cases when the leakage restarts every time the hole is redrilled after cementing. One way is to pump into the hole saw-dust, sometimes mixed with the cement.

In some cases it has proved successful to pump down a mixture of bentonite and crude oil, as it forms a viscous jelly when heated.

In cases of extreme leakage the coarser the material pumped down the better, but piston pumps have a very limited capacity for pumping coarse material.

There are available special pumps (grouting pumps) capable of pumping fairly coarse material, and it would certainly be a great asset to have such a pump. They are not all that expensive, but could save a lot of time and rroble.

Besides closing off leakages cementing is used for supporting the walls of the hole to prevent their caving-in on the drill bit and as already mentioned, the casing is cemented in the hole.

In several instances it has been observed that the cement did not harden in the drillholes. Being well known abroad this phenomenon has so far received little attention in Iceland. A probable reason for this is that at high temperatures the chemical process in Portland cement does not proceed as expected.

If the temperature is not very high, such as in drill rods when the cement is pumped down, the setting time is appreciably shortened and the cement may stiffen in the drill rods creating friction to the degree that pumping becomes impossible.

Testing and experience abroad have revealed that the setting time of cement is shortest at about 110°C, being again prolonged at higher temperatures. In order to obstruct this process a retarder which slows the hardening, such as betonite together with plasticizer which softens the cement, can be added to the cement. To make the cement harden at high temperature it has proved successful abroad to mix into the cement crushed diatomite as much as 30% of weight.

1.2.3 Drilling plan for a production well in Námafjall or Krafla.

Drill: Gufubor

Casings:

Surface casing	16"	55	lb/ft	Grade	H40	approx.	30 m
Safety casing	13 3/8"	48	"	"	"	"	0-200 m
Production casing	9 5/8"	36	"	"	V55	"	300-400 m
Liner, slotted	7 5/8"	24	"	"	"	"	1600-1800 m

Percussion drillhole, 18" diameter, drilled down to approximately 30 m depth and provided with "surface casing", the casing being cemented between hole wall and pipe from top.

Drilling valve and steam-blow preventer are fitted on the surface casing. A 12 1/4" drill bit used down to 100 m depth, flush water leakage that may occur during this drilling is closed off with cement and other means at our disposal.

When the drillhole has reached 100 m depth and all water leakage been repaired the hole is pressure tested. Preventer is locked around the pipes and pressure applied to the hole. The pressure is decided by the depth of the hole and shall be 0.15 x depth of hole (m) measured in kg/cm^2, thus at 100 m depth the test pressure is to be 15 kg/cm^2. After having been pressure tested with satisfactory results at 100 m depth drilling is continued with the same drill bit diameter and the hole is pressure tested as described above at suitable intervals down to 200 m.

The pressure testing is performed to ascertain that the hole walls will not give way when the casing is cemented.

According to the equation the test pressure is about 25% higher at the bottom than corresponding pressure from cement. On the other hand the test pressure is somewhat greater higher up in the hole, which could result in the hole walls giving way when pressure tested although having withstood pressure testing at shallower depth. This liability could be met by using a packer when testing, but that would probably mean too slow a procedure.

Should unmanageable circulation water leakage occur in the drilling down to 200 m depth it is possible to open the hole to 15" with a hole opener and then case it with a safety casing somewhat deeper than the leakage.

The cementing of safety casing is done by first putting down through the casing a quantity which would easily fill the space between the casing and the hole wall up to the opening. When the amount is supposed to have reched this limit the pumping of cement is stopped for about 10 minutes, the pumping then resumed and the process repeated, with a small quantity of cement each time, until the pressure begins to increase. Great care must be taken not to let the pressure increase to the limit of danger of hole walls giving way. Finally cement is pumped down outside the pipe from above.

When the hole has been secured sufficiently down to 200 m depth, whether by a safety casing or not, drilling is resumed with a 12 1/4" drill bit and all leakage closed off as far as possible.

After 300 m depth is reached drilling is continued to the next unmanageable leakage, yet not deeper than 400 m. If excessive circulation water loss occurs the bottom of the hole shall be cemented to secure it against leakage. Afterwards the hole is pressure tested and close attention paid to leakage and its location.

When it is considered certain that an anchor casing can sucessfully be fully cemented by way of cement being pumped down through the pipe and upwards on the clearance side then the anchor casing is put in, after which water is pumped through the hole for a considerable time to cool the walls of the hole. Now the anchor casing is cemented. Sound and continuous cementing outside the pipe is essential as faulty cementing outside an anchor casing can cause irredeemable damage to the hole.

The quantity of cement to be pumped down the casing must be such that there is no doubt of it being sufficient to fill all available space. Although some cement may be wasted (maximum 20 tons of cement) the cost is negligible comparing to the possible consequences of poor cementing.

Anchor casing is cut apart at a suitable heigh above the next joint (about 30 cm) and a 10" ser. 600 flange welded to the end of the pipe. The flange on the anchor casing is closed and the hole pressure tested with as much as 60 kg/cm^2 pressure. The pressure test is performed in order to test the flange on the anchor casing. Now the final wellhead is fitted to the hole top, i.e. a spool and a 10" ser. 600 gated valve.

From this stage onwards a 8 3/4" drill bit is used and little attention payed to leakages in the hole except when cuttings are poorly washed from the drill bit. The well is drilled to about 1800 m depth, but the final depth depends on the capability of the drill rig and the permeability of the rock. When full depth is achieved a liner is suspended in it. The liner is suspended on a special liner hanger about 30 m high in the anchor casing and slotted where considered necessary due to aquifers in the rock.

There is reason to belief that the liner should extend almost down to the bottom of the hole.

1.2.4 The output of drillholes.

The number of wells needed to supply the steam required from the power station largely depends on the temperature and quantity of steam from the holes. The amount of steam obtained from each drillhole depends on various conditions in the thermal area, the major factors being the temperature of the water emanating from the hole and the permeability of the rock.

In the area at Námafjall and Krafla drilling penetrates down to aquiferous strata, containing water at temperatures of 260 - 290^{o}C. While ascending through the hole the pressure decreases whereby a part of the water flashes to steam. As the volume of the steam is many times that of the water it is essential that the upper part of the hole is sufficiently wide.

Experience gathered in Námafjall is relied on in estimating the quantity of steam from drillholes in the area. In July 1968 discharge measurements were carried out on drillhole 3 by critical pressure method, i.e. the drillhole is made to blow through a pipe of a certain diameter and the pressure in the outlet measured. The results of these measurements showed the output to be 6 - 8 tons/hour of steam at back pressure 11 - 6 ata. The hole was not used from early 1969, and after having been closed for one year, its output, when tested again in early 1971, had fallaen to almost zero. The decrease in its capacity might be due to the fact that deeper holes located close to hole 3 are drawing water from the same aquiters. Yet the output of hole 5, which is of equal depth to No 3, has not decreased. In July 1969 drillhole 4 was measured in an identical way the result being 25 to 30 tons of steam at the above back pressure.

Measuring equipment, which registers steam flow, was then fitted to the system and thus the steam flow to the electric power station and the diatomite plant is continnously recorded. In February 1971 measurements were made on drillholes 4, 5 and 9 and the quantity of steam recorded at different pressures at the location of delivery for ustilization. The characteristic curves for these drillholes are drawn in Fig. 10, but some errors can be expected because if a change occurs in the back pressure of a drillhole a long time may elaspe before the hole regains equilibrium.

In long term measurements wells 4, 5 and 9 give 51 tn/hour at 7,8 ata back pressure at the place of delivery. In the same way wells 7 and 8 give 35 tn/hour at 10,5 ata back pressure. According to the characteristic curves for wells 4, 5 and 9 their discharge is reduced by half by increasing the back pressure from 7, 8 ata to 10,5 ata. In May 1971 wells 4, 7, 8 and 9 were all connected to the diatomite plant and then the quantity was measured 35 tn/hour at 11 ata back pressure indicting that the output of the wells decreases rapidly with increased back pressure.

Well 9 is considered to be located at the northern margin of the thermal area as it is not as hot and productive as the other wells. Wells 4 and 5 are here considered to represent an "average" well and their output of steam taken as what may be expected in general.

This is a fairly conservative estimate as the wells in question are relatively narrow and shallow. The present project, however, proposes considerably deeper and wider wells to be drilled.

1 3 Climate.

To render the geothermal resources of a thermal area utilizable for generation of electricity with opimum efficiency by available equipment, it is necessary to be able to supply a great quantity of cooling water, or about fourty times the steam requirements of the power station.

Surface water is not available for these purposes and there are no other possibilities than a closed circulation system. In a closed system the cooling water is circulated between that or those parts, which need cooling, where the temperature rises, and a cooling tower or spray pond, where its temperature falls to the same degree. The recooling in a cooling tower or pond is dependent on the climate of each particular area, i.e. air temperature, humidity, wind velocity and prevailing wind direction, Weather observations have not been carried out in the thermal areas in question, therefore data from other weather stations must be relied on. Tables 1 - 5 on pages 19 to 21 illustrate an excerpt from the reports of the Weather Bureau from the years 1931-1960.

The design of a cooling tower or pond must take into account the possibility of cooling a certain body of water down to a certain temperature level, comparatively independent of weather conditions. The higher the chosen design values for air temperature and humidity are the larger the size and consequently higher the cost of the cooling tower will be. The same also applies to a spray pond where the design value for the wind velocity has to be considered too. The lower the chosen wind velocity the larger and more expensive the pond becomes.

Table 1, page 19, shows that July is on the average the warmest month throughout the country, with 8.9°C - 11.2°C. Most likely the average temperature of July in these geothermal areas is somewhat like that at nearby localities such as Reykjahlíð or Grímsstaðir, i.e. approximately 9.5°C. Information on the mean values of daily deviations from the above average temperature for July are only available for Reykjavík, these are shown in Table 2, page 20. From Tables 1 and 2 it can be deduced that the daily range of the temperature is within the limits 11.2° + 1.5°C and 11.2° - 1.9°C as average for Reykjavík. The daily temperature variations probably increase with distance from the sea and as to the Mývatn area that difference is estimated to be about - 1°C. According to this the daily range of the temperature in the thermal areas in question should fall within the limits 9.5° + 2.5°C = 12°C and 9.5° - 2.9°C for an average year.

To make the power station able to operate at full capacity permanently the cooling system must be designed for higher temperature than the mentioned 12°C. In order to give an indidation of how much higher that temperature should be the results of studies on the mean values for daily maximums are illustrated in Table 3, page 20. It reveals that the average daily maximums in July for Reykjavík was 14.7°C or 2°C higher than the abovementioned average. On the basis of the same assumptions as above, i.e. expecting greater deviations from the mean value in the interior than in coastal regions of the order of ± 1°C one can expect a mean maximum of 12° + 3° = 15°C in the thermal areas. For comparison it is worth mentioning that during the interval 1949 - 1953 about 10% of all temperature measurements in Reykjavík proved to be in the range 11° - 19°C, but only 1% in the range 16° - 19°C. Taking account of this the power station should manage to operate comparatively continuously independent of air temperature during summer on the basis of the design temperature being 15°C.

Table 4, page 21, illustrates the mean humidity in Reykjavík. The mean humidity for July, the time when maximum air temperature can be expected, is 73 - 79%. In the thermal areas the humidity of the air is probably on average lower than in Reykjavík due to their distance from the sea. Since the figure is a mean value it is considered advisable to put the design value of a cooling system at 80%.

In Talbe 5, page 21, is shown the frequency of wind directions and average wind velocity at Grímsstaðir. The average wind velocity for July is according to the table 2.3 m/s while the frequency of calm weather is 17%. In calm weather the cooling capacity of a spray pond is practically none, and this inevitably leads to reduced output capacity of the station. This will be further discussed in section 2.4.

Table 1

Mean temperature 1931 - 1960, ^{o}C.

Month	Reykjvík	Húsavík	Reykjahlíð	Grímsstaðir
1	-0.4	-1.2	-4.1	-4.8
2	-0.1	-1.3	-4.2	-4.8
3	1.5	0.0	-2.4	-3.1
4	3.1	1.5	-0.3	-1.1
5	6.9	5.7	4.7	3.7
6	9.5	8.6	8.2	7.2
7	11.2	10.2	10.2	8.9
8	10.8	9.8	9.3	8.0
9	8.6	7.9	6.5	5.4
10	4.9	4.0	1.9	0.9
11	2.6	1.6	-1.0	-1.8
12	0.9	-0.2	-2.9	-3.6

Table 2.

Daily temperature variations in Reykjavík 1956 - 1960, °C.

Month/hour	2	5	8	11	14	17	20	23
January	-0,1	-0,1	-0,2	-0,1	0.2	0,1	0,1	0,1
February	-0,4	-0,3	-0,5	0,3	0,9	0,5	-0,2	-0,3
March	-0,8	-0,8	-0,8	0,6	1,3	1,0	0,0	-0,5
April	-1,2	-1,5	-0,6	1,0	1,6	1,3	0,2	-0,8
May	-1,8	-1,9	-0,3	1,0	1,8	1,5	0,6	-0,9
June	-1,6	-1.5	-0,3	0,9	1,4	1,2	0,5	-0,6
July	-1,6	-1,9	-0,3	0,9	1,5	1,4	0,6	-0,6
August	-1,7	-2,1	-0,6	1,0	1,9	1,7	0,7	-0,9
September	-1,1	-1,2	-0,7	0,9	1,6	1,3	0,0	-0,8
October	-0,6	-0,7	-0,6	0,5	1,2	0,8	-0,2	-0,4
November	-0,2	-0,3	-0,1	0,3	0,6	0,0	-0,1	-0,2
December	0,0	0,0	-0,0	0,1	0,0	0,0	0,0	-0,1

Table 3.

Daily mean minimum mean maximum temperature 1931 - 1960, °C

Month	1	2	3	4	5	6	7	8	9	10	11	12
Station:												
Reykjavík	-2,8	-2,8	-1,2	0,6	4,1	7,0	9,0	8,3	6,2	2,7	0,3	-1,6
	2,4	2,8	4,6	6,4	10,3	12,9	14,7	14,1	11,6	7,7	4,9	3,5
Akureyri	-4,7	-4,7	-3,4	-1,3	2,9	6,0	7,9	7,4	4,9	0,9	-1,5	-3,4
	1,8	1,5	3,1	5,3	10,2	12,8	14,3	13,9	11,2	6,7	4,1	2,6

Table 4.

Mean humidity in Reykjavík 1949 - 1953, % R.F.

Month hour	2	5	8	11	14	17	20	23
January	82	81	81	80	81	82	82	82
February	85	85	85	84	83	83	83	84
March	83	83	82	79	78	80	82	72
April	81	81	79	76	74	74	79	81
May	83	82	75	71	69	70	75	81
June	84	83	75	70	69	70	74	80
July	86	85	79	75	73	75	78	83
August	85	86	81	74	71	73	79	84
September	85	85	83	79	76	77	82	84
October	83	82	83	81	78	80	82	83
November	81	82	83	81	79	81	81	81
December	83	83	82	81	81	81	82	81

Table 5.

Wind direction frequency

and mean wind velocity in Grímsstaðir 1931 - 1960.

Month	m/s	N	NE	E	SE	S	SW	W	NW	Calm
January	3,3	11	10	10	22	12	16	2	4	13
February	3,3	13	13	6	20	14	15	2	4	13
March	3,1	10	11	8	23	15	14	2	4	13
April	3,1	15	11	8	17	13	13	3	7	13
May	2,8	19	9	10	20	14	12	2	4	10
June	2,5	25	9	8	14	12	11	1	5	15
July	2,3	26	11	7	13	12	9	0	5	17
August	2,3	24	10	7	12	14	12	1	4	16
September	2,5	14	7	8	17	17	14	1	6	16
October	2,6	13	7	5	22	19	12	1	5	16
November	2,8	11	9	6	21	17	12	2	5	17
December	3,1	11	11	8	23	14	14	1	4	14

2. Power Station.

2.1 Type.

The utilization of geothermal steam for electricity production was initiated in Italy shortly after the turn of the century. At present the overall production capacity of geothermal power palnts in the world amounts to about 1200 MW while plants of about 1000 MW capacity are being planned for the next few years.

Common to all these stations is the use of steam turbines for activating the generators, and the harnessing of the well energy is by means of one of the following possibilities:

System 1	Back-pressure turbine
System 2	Condensing turbine without the use of drillhole water (where available).
System 3	Condensing turbine with the use of drillhole water.

Fig. 11 is an explanatory chart of system 1. The steam is diverted to the turbine at pressure p_1 and away from it again at about 1 ata pressure, p_2. Where the wells yield both water and steam simultaneously, as is the case in Iceland, the water is separated from the steam in special steam separators and disposed of unused.

Fig. 12 is an explanatory chart of system 2. This system is different from system 1 by instead of letting the steam excape at about 1 ata pressure it is condensed in a condenser at a considerably lower pressure, p_2 (about o,1 ata), whereby its thermal content is appreciably more efficiently used. The drillhole water is disposed of unused as before.

Fig. 13 is an explanatory chart of system 3. This system is based on wells yielding both water and steam at the same time. The steam is used in the same way as in system 2, at pressure p_1, while the drillhole water is made to boil at a lower pressure, p_3, whereby a certain steam flow is obtained and utilized for produciton of electricity. In the explanatory chart a special turbo-generator is supposed to utilize this steam flow, but it is also possible to use only one unit designed with a double - inlet turbine, one for "high-pressure steam" and another for "low-pressure steam".

The efficiency in utilizing the well energy is very different from one system to another. On defining the efficiency as 100% when all discharge water of the station is disposed of at 45^{o}C the corresponding efficiency, n_t, of above systems is as follows:

System	P_1	P_2	P_3	n_{is}	n_m	n_t
1	6.0	1.0		80	90	3
2	4.0	0.1		80	90	7
3	4.0	0.1	1.0	80	80	10

P_1 : steam pressure at main valve of "high-pressure turbine" ata.
P_2 : steam pressure at outlet of turbine, ata.
P_3 : steam pressure at main valve of "low-pressure turbine", ata.
n_{is}: isentropic efficiency of turbine, %.
n_m : mechanical efficiency of turbine, %.
n_t : thermodynamic efficiency of turbine, %.

As can be seen efficiency in using the thermal energy is in all cases very low, but the n_t for system 2 is more than twice as high and for system 3 more than three times as high as for system 1.

A system 1 power station is very simple as a condenser with corresponding cooling water system is not needed. The capital cost of machines is therefore low compared to systems 2 and 3, but the required quantity of steam is great.

A system 1 power station would be suitable where power requirements are comparatively low (1000-1600 KW) and/or if it were not to be operated continuously (i.e. a reserve power station). A unit of this type could for example be used in geothermal areas while research is carried out, as the machines are easily transportable.

A system 2 power station is a considerably complex operation as a condenser is needed with appurtenant cooling equipment. The capital cost of machinery becomes considerably higher for this type of station than for a system 1 station, but it produces 130% more electricity from the same amount of steam. This system is most common in stations generating electricity in competition with other types of electric power stations, for example in Lardarello in Italy, a part of Wairakei in New-Zealand, Geysers in California and Matsukawa in Japan. The size of each turbo-generator ranges from about 8 MW to 55 MW.

A system 3 power station can be considered as an extension of system 2, comprising a steam boiler and a "low-pressure turbine" together with accompanying plumbing. Such an extension would increase the capacity of the station by over 40% without needing extra wells. As mentioned earlier the two "single-pressure turbines" could possibly be replaced by one "double-pressure turbine", a method which would undoubtedly be the most economical one should the station be designed according to system 3 initially. A part of the Wairakei power station comprises such 30 MW units and identical 20 MW units are planned to be installed in El Salvador in this year (1972).

This preliminary project report is designed for a 8 - 16 MW development stage, which most likely is too small to make system 3 more economical than system 2. It must also be considered unadvisable to construct an expensive geothermal power plant while sufficient experience has not been gained in harnessing high-temperature thermal areas in Iceland. Yet it should be mentioned that in El Salvador experiments are being carried out on the transmission of water and steam along the same pipe, which, if successful, would reduce the installation cost of system 3 appreciably. This is a possibility certainly worth keeping in mind should a desicion to proceed with the station be made.

As mentioned above a system 1 thermal station of 8 - 16 MW capacity is almost out of the question since the excessive steam requirements of such a station would result in a higher operation cost than for a system 2 station of the same capasity in spite of the capital cost being only 60% of the total cost of such a station.

According to the above said this preliminary project report is based on a system 2 power station. The main decisive factors for the capital- and operating cost of such a station will now be discussed further.

2.2 Turbine.

A turbine to be used in a geothermal power station must be specially designed taking into account that the steam is almost saturated; is under low pressure and contains uncondensable gases and salts. In the low pressure portion of the engine the steam has become wet (10 - 13%), and consequently, the speed of the turbine blades (tip speed) has to be restricted to about 275 m/s in order to reduce erosion in the low-pressure portion. Such a speed limit is also desirable because of the chlorine content of the steam which causes stress corrosion, especially in case of high speed and consequently high stresses. The material of the turbine blades must be selected with special regard to these conditions, a 12 - 14% chrome-steel alloy in soft state has been used with good results in the Wairakei machines. A possible alternative is to design the low-pressure portion with special steam separators, which remove a part of the water content of the steam thereby reducing the danger of erosion. It might also be advantageous to fit erosion screens on the last blade row for the same purpose.

Other things being equal a reaction turbine is more suitable than an action turbine as the corrosive effect of the steam on the turbine axis is then reduced.

The H_2S content of the steam makes copper alloys unsuitable for seals and practically everywhere where the steam comes in contact. In order to reduce the H_2S content of the air inside the power station it would be desirable to have a double flow turbine. In that case there is no labyrinth - seal in the high-pressure portion, and furthermore the prerequisites of slow blade speed at 3000 rev./min. will then be more easily fulfilled.

To prevent precipitation of silicia in seals in might be plausible to let pure steam, obtained in a heat exhanger, flow through them. For the same reasons it is desirable that the main valves on the steam inlet be double to make it possible to remove them for cleaning without having to stop the engine.

It is possible that the selected machine inlet pressure will not prove suitable. The output capacity and pressure of the wells might fall with increased exploitation of the thermal area with an increased number of wells making it necessary to reduce the inlet pressure in accordance with the characteristic curves for the wells (see section 2.2.1.). In case it should be considered advantageous to alter the system, i.e. system 2 into system 3 it might also be suitable to increase the turbine inlet pressure.

With this in mind it would be advantageous if it were possible to remove or insert additional stages into the high-pressure portion of the machine without significant additional expenditure, with the result that the machine could obtain full efficiency in spite of the pressure being about 1 kg/cm^2 higher or lower than the design pressure.

2.2.1 Steam pressure at turbine inlet.

The steam pressure in question is the one called p_1 on explanatory chart for system 2, Fig. 12; at this pressure the machine is expected to work at full efficiency. As already discussed in section 1.2.4 measurments of the steam discharge of wells 4, 5 and 9 were carried out in Bjarnarflag at Námafjall. Pressure and quantity was read of gauges in the geothermal power station, thus, according to explanatory charts of systems 1 and 2, Figs. 11 and 12, the recorded pressure is p_1, but not p_0 as is most common in such measurements. The output capacity of well No. 9 was appreciably lower than for wells 4 and 5, and until more extensive recordings of other wells over a longer period of time have been accomplished the mean steam discharge of wells number 4 and 5 is assumed to represent an "average well" in the geothermal area.

Within the pressure range applied in the measurements, 6 - 11 ata, the steam characteristic curves proved to be straight. Assuming that the same applies for the range 2 - 6 ata, the above "average characteristic curves" of the thermal area were extended down to 2 ata.

For a given value of condensing pressure, p_2 (see explanatory figure of system 2) and at fixed isentropic and mechanic efficiency values of the turbo-generator, the total output capacity of the station at different inlet pressure values, p_1, can be calculated. The results of these calculations thogether with the "average characteristic curves" referred to above are exhibited in Fig. 14. The condensing pressure was selected 0,07 and 0,10 ata and the factor of isentropic and mechanical efficiency was selected 1,00 or a 100% efficient machine. The isentropic and/or mechanical efficiency of the machine is probably independent of the pressure p_1, therefore the shape of the curve does not depend on what values are selected in this case. As can be seen the energy of the well reaches a maximum at about 3 ata, which means that the operating pressure at a well, p_o, is about 4.5 - 5 ata, assuming 1.5 to 2.0 kg/cm^2 pressure drop in pipes and separators.

Should 3 ata be selected as turbine inlet pressure the capital cost of wells would surely be at minumum, but the same does not apply to other parts of the power station. The lower the selected inlet pressure the more cumbersome and expensive the turbine and the condenser becomes, thus, before making the final choice, the minimum total cost of turbine, condenser and well arrangement must be found.

As mentioned earlier the basis for a decision of an "average well" is very unsatisfactory, and also it is quite uncertain whether the future pipes network will be similar to that of the existing power station in Bjarnarflag. It is therefore evident that accurate cost estimates cannot be made at this stage, so a guess it justifiable when deciding the inlet pressure on which the cost estimate is based.

4 ata ate regarded to mark the lower limit of the pressure range within which final operating pressure would be selected, which means that the estimated capital cost of engines will be rather high, while the cost of wells and steam price will be fairly low.

The total energy of the "average wells" cannot be calculated according to system 3 as water discharge measurements have not been made yet. Yet it is quite certain that the total energy will be at its peak at higher pressure than 3 ata, something that should be kept in mind if the application of that system is to be anticipated at a later stage.

2.2.2 Pressure of condenser.

As exhibited in Fig. 14 the condensing pressure, p_2, greatly affects the output capacity of the turbo-generator. Thus a 0.03 kg/cm^2 decrease, from 0.10 ata to 0.07 ata, would result in about 10% increase in output, other things being equal. Yet it should be noted that the lower the selected condensing pressure, the larger the diameter of the "low-pressure" becomes and the wetter the steam in the last steps. This implies that the condensing pressure must be limited to 0.10 - 0.07 ata to make it possible to satisfy the above mentioned demands of moderate stress and safety against erosion.

In section 1.3 the design values for weather factors were selected 15°C and 80% humidity. This choice of course limits the temperature of the cooling water and consequently the condensing pressure, as discussed in section 2.4.

2.3 Condenser.

One of the aspects in which a geothermal power station differs from a conventional steam power station is that the the condensate need not be reused. Therefore the steam can be condensed by direct cooling, i.e. by spraying the cooling water into the steam jet from the turbine. This offers both the most convenient and the cheapest solution available as a heat exchanger between steam and cooling water, which increases the temperature difference between the cooling water and the condensate and makes the condenser expensive both as regards construction and maintenance, is not needed.

There are two alternatives for maintaining vacuum pressure in the condenser, firstly by a pump, and secondly by a water column ("barometric" condenser).

The former alternative introduces the danger of water entering the turbine in case the pump fails, in addition the pump has to be positioned at a considerably lower level than the outlet of the condenser to prevent cavitation.

The latter alternative has the advantage of eliminating the danger of water entering the turbine. The condenser can be arranged in two ways, either it is positioned below the turbine or placed laterally and above the turbine. In the former case the turbine has to be at about 12 - 13 m height above the floor of the power house, but in the latter at 6 - 7 m with a connection pipe between turbine outlet and condenser inlet. It should be noted that a level floor is assumed, but if there are considerable elevation differences in the topography it is possible to place the condenser below the turbine, without the power house becoming very high.

Although a condenser with a barometric tube may require a higher and more expensive power house than a condenser using a pump, the operational reliability of the former is such an important asset that the latter altenative hardly counts.

It is debatable, however, whether it is more suitable to place the condenser below or above the turbine. The main assets of the former alternative ar firstly that the condenser is indoors and therefore no danger of ice formation in gas pipes. Secondly the pressure drop between turbine outlet and condenser is negligible and installation is easy as the power house crane can be used. The main liability of the arrangement is the rather high power house it demands, 22 - 24 m.

The main asset of the latter alternative is the lower power house, 16 - 17 m, whereas the main liabilities are firstly that the pressure drop in the pipe between the turbine outlet and condenser inlet causes considerable difference between condenser pressure and outlet pressure. Thus in order to obtain the same turbine output for a high level condenser as for a low level one the condensing pressure of the former has to be lower to the same degree as this pressure drop. The condenser is also difficult to install in this case, besides the danger of damages due to frost.

It is considered advisable to accept both these alternatives as tentative possibilities. Figs 15 and 16 exhibit plans and sections of a power house illustrating this difference in location of the condenser and the cost estimate takes notice of both possibilities.

The steam contains about 2 l/kg of uncondensable gases (20°C, 760 mm Hg), which have to be removed from the condenser. The gas content does not necessitate the use of turbo compressors as steam and water ejectors will suffice. Steam ejectors are sheaper in operation and a more common product, but danger of corrosion of intercoolers requires special care in selection of material and maintainance, leaving both options acceptable. The cost estimate assumes two-step steam ejectors. Experience abroad has revealed that the gas content of natural steam varies, may both increase and decrease, therefore the steam ejectors are designed with a capacity of double the amount of gas observed so far.

2.4 Cooling system.

There are two main alternatives for the cooling of circulating water:

a) Spray pond

b) Cooling towers

Cooling in a spray pond is done by spraying hot water from the condenser into the air above a spray pond whereby a part of it evaprates while a greater part of it returns to the pond after having been cooled due to evaporation and convection. To have the ability to transfer heat the air must be in such a state as to be capable of absorbing moisture and heat, i.e. the lower the moisture content and temperature of the air the more vigorous is the cooling. Thus it is evident that the air above the pond must be moving in such a way that saturated air is replaced by dryer and colder air. As stated in section 1.2 the mean wind velocity for July at Grímsstaðir is 2.3 m/s, and the design values of air temperature and moisture were 15°C and 80%. Calculations indicate the areal of a spray pond to be about 800 - 1000 m^2/MW. In still weather the temperature of a spray pond will rise about 2 - 3°C/hour, assuming a 1.5 m deep pond. As an example it can be mentioned that still weather lasting for 3 hours would reduce the output of the power station by about 10%. Recorded calm weather at Grímsstaðir was 17% for July. It is therefore evident that some variations in the power output of the station cannot be avoided, should a spray pond be relied on solely.

Cooling towers are based on the same principles as the spray pond except that they are to a large degree independent of the local wind velocity. There are two main types of towers, self-draught towers and air forced towers. The self-draught towers are voluminous as the air current is maintained by a chimney effect, but their operation is less expensive. During spells of severe frost there is danger of ice accoumulation in the air intake of the tower, which could easily cause serious operational disturbances in the station.

The air current through the air forced tower is maintained by an axial blower not requiring as much space as the former alternative, while on the other hand the operation cost is fairly high. If ice forms in the air intake of the tower the rotation of the blower can be reversed whereby it deices the intake.

Under normal conditions and favourable circumstances for constructing a spray pond it would be the cheapest solution, but an air forced tower the most expensive. With regard to the fact that a spray pond is dependent on wind velocity and there is a constant danger of slush ice formation during winter it is not considered advisable to choose this alternative, although it may be cheapest.

The above-mentioned advantages of blower cooling towers over self-draught towers during winter makes them the only possible solution for a closed cooling system; the cost estimate will be based on this cooling method.

To make the steam condensable at about 0,07 ata in the condenser, the temperature of the disposal water of the condenser, which simultaneously is the inflow temperature of the cooling tower, must necessarily be about 4°C lower than boiling temperature of water at 0.07 ata, i.e. 34°C. The "wet temperature" of the air at 15°C and 80% moisture is 13°C. The size and cost of a cooling tower increases with decreasing difference in the temperatures of the disposal water of the tower, which at the same time is the inflow temperature of the condenser, and "wet temperature" of the air. Usually cooling towers are designed for about 5 - 10°C difference whereby the disposal water temperature becomes 18° - 23°C and the cooling water demand of the condenser 260 - 380 m^3/Mwh.

In the cooling tower some water is lost through evapration and drizzle formation. Under normal conditions about 2% of the water flow is lost, but as steam condensation in the condenser is about 2.5% of the water flow about 0.5% need to be diverted from the system. The condensing water is acidic and contains some minerals, but it has not been studied whether the cooling water needs chemical handling, and that factor is not accounted for in the cost estimate. It is clear, however, that special care is needed in the choice of cooling system material. The cooling tower must necessarily be protected against corrosion, e.g. by epoxy-filming.

If the tower can possibly be positioned in such a way that the water table inside it is approximately 3.5 m below the inlet for cooling water of the condenser, only one pair of pumps is needed for pumping cooling water from the outlet well of the "barometric" tube up to the sprayers of the cooling tower. For safety reasons two pumps are provided, each one capable of pumping 100% of the total water quantity.

The positioning and type of pumps can be varied to suit the local conditions at the site of construction. In the cost estimate they are proposed to be placed outside the powerhouse in a detached pumphouse.

2.5 Steam pipe network.

In the design of well equipment and steam piping network attention must be payed to the frequent blizzards and severe frost during winter in the Krafla and Námafjall areas.

Fig. 17 illustrates the arrangement of the steam separator. As a mixture of water, steam and a small amount of sand are emitted from the wells a pre-separator is located at each wellhead, i.e. a U bend as exhibited in the figure.

In the pre-separator the sand and as much as 80% of the water accompanying the steam are separated from it while the steam and some water is transmitted along the steam pipe to the main separator where the mixture enters the separator cyclone tangentially and is separated by centrifugal force. The water from the separator flows through a so-called float valve, which is controlled by a pontoon in the water tanks. This float valve is specially designed with regard to the uneven steam requirements of the Diatomite Plant whereby the steam pressure in the separator varies up and down, thus the quantity of the outflowing water is variable.

Operational experience has, however, shown that all moveable parts inside the separator endure badly and the maintainance of the float valves is heavy; it is now planned to abondan their use in favour of a multiple valve system so that the water flow may be controlled by fixed settings.

The maximum pressure of the steam separator and steam system is controlled by two safety valves connected to the steam system where the steam flows from the separator into the steam pipe. The safety valves open at pressure somewhat higher than the operational pressure of the system.

Initially the well equipment was kept outdoors, but on basis of experience a shelter was built, which furthermore has considerable insulation value in bad weather. The pipe network is suspended in 2 m elevation above ground to prevent the accumulation of snow at the pipes and to avoid meltwater.

The temperature of the steam in the pipes is up to 180°C and as the temperature outdoors can be as low as -35°C thermal expansion of the order of 9.25 - 0.26 m/100 m can be expected. The steam transmission pipes are suspended on concrete poles at 100 - 200 m intervals, but in between the pipe is supported by guy rods with turn buckles, see Fig. 17. The thermal expansion is absorbed by compensators positioned at the poles.

The pipes are isolated by 1 1/2" thick glass fibre covered on the outside by an aluminium film, to protect the insulation from moisture.

2.6 Electrical system.

In Fig. 18 is shown a diagram of electrical connections. It is in all main respects identical to those of usual hydro-power stations; the main difference being a comparatively large powerhouse transformer.

A 66 KV. transmission line is expected to run from the station to Mývatn and from there to a transformer station at Laxá. A diesel power station, connected to a 300 KVA poverhouse transformer, will supply the station with reserve power.

The H_2S content in the atmosphere over thermal areas necessitates special arrangements for protection against corrosion. These precautionary measures would primarily be the choice of correct material and finish. As an example can be mentioned the metal coating of delicate switches, protection by oil bath and airtight finish.

The H_2S content inside the powerhouse may also be controlled by an appropriate ventilation system. A closed ventilation circuit is e.g. proposed for the alternators.

2.7 Power house.

In the initial planning of the power house emphasis was laid on possible future extension of the station and a simple and inexpensive form of construction, easily adaptable to various different local conditions at a site of construction.

The house is divided into two main sections, turbine house and workshop and control room.

The turbo-generators are placed across the long axis of the turbine house, which is a normal location with regard to the switchgear being parallel to the long side of the control and workshop room, while cooling towers and pump house together with steam separators are positioned parallel to the long side of the turbine house. There are facilities in the end of the turbine house for putting down the lagest parts of the machine units during maintenance or inspection, and between units enough space is left for steam ejectors.

The control panel will be in the control and workshop building where there will also be space for the electrical gear and staff accomodation together with a workshop intended for repairs.

A future extension of the station for housing one additinal turbo-generator is possible without enlarging the control and workshop building.

As mentioned earlier the cost estimate accounts for the two types of condensers separately.

It is customary to locate the control panel on the same floor as the turbo-generator, but in case of a low level condenser the roof elevation on the lower floor of the control and workshop building becomes unnecessarily high. It is not considered essential to have the control room on the same floor as the turbine platform, thus an equally high control and workshop building is proposed regardless of the type of condenser.

The preliminary design of the powerhouse was prepared by S. Thoroddsen and Partners, consulting engineers, and further information in that respect are to be found in their report: "Geothermal Power Station at Krafla; Preliminary Plan of Power House". It is to be mentioned that S. Thoroddsen and Partner´s cost estimate considers the control room to be stationed at the same level as the turbine platform regardless of wether the condenser is a low- or high level type. In the following cost estimate this arrangement was altered in accordance with what has been said above. Furthermore the entire building is now expected to be insulated, not only the upper floor of the control and workshop building as proposed in the earlier plan.

2.8 Location.

The present estimate is not based on any special site for the power station inside the general Námafjall and Krafla areas.

It was mentioned earlier that uneven topography was suitable for a thermal power station as the powerhouse would be lower and the circulating water system more simple. Such circumstances are to be found in the above geothermal areas. The drawing of power- and pumphouse therfore take into account such a site.

An accurate cost estimate of building can certainly not be made until their location is decided and the foundation thoroughly investigated; the cost estimate for buildings must therefore be regarded with due respect to this fact.

While estimating which locality, Námafjall or Krafla, is more suitable for a station various factors must be considered.

Assuming that both thermal areas as such are equally well suited, the major asset of the Krafla area is the lower probability of environmental pollution caused by the disposal water.

As to disadvantages a road must be constructed from the inhabited district to the Krafla area, cf. S. Thoroddsen and Partner's report: "Road to Víti". The transmission line will also be longer and certainly locating the station in an uninhabited region involves several obstacles.

3. Time of Constuction.

The power station is scheduled to be put into service in about 43 months from the date of the decision to proceed with the work.

The controlling factor is the design and construction of the turbine, a time schedule for which is shown in Fig. 19.

As can be seen various decisions and studies must be made before the preparation of bidding documents can begin. Above all a site has to be decided upon before the final choice between a high level condenser and a low level type is made. Well sites must be selected for determining the operating pressure at turbine inlet. A decision has to be made on the system according to which the station is to be built, cf. 2.1. The circulating water system must be studied with special respect to chemical properties of the cooling water and the disposal of hot drillhole water must be carefully planned with regard to pollution and the possibility of diverting it back into the geothermal reservoir through special holes (reinjection).

When this is accomplished the final touch can be put on the bidding documents. As explained in Fig. 19 the design and construction of the turbine absorbs more than half the total time of construction, or 22 months, transportation and construction about 8 months, and delivery and output trials about 3 months.

It is clear that a decision to proceed with the contruction of a power station cannot be made until the necessary preparatory rescarch has been completed. This applies especially to the Krafla area where the drilling of at least one or two exploratory wells is necessary. It would also be desirable to make experiments on the materials considered most suitable for the various parts of the power station, with the purpose of studying the effect of the steam and condensate with regard to corrosion, precipitations and strength.

Keeping in mind that drilling and research in remote areas must be carried out during summer due to weather, it is considered unlikely that a well-founded decision to construct a power station can be made until a year after the above explorations and drilling started, and probably still later should the Krafla area be selected.

4. Cost Estimate.

4.1 Capital.

The following cost estimate is based on the price of materials and labour as in early 1972.

Imported materials are expected to be exemted from customs and as well as labour exempted from sales tax.

The following items are not considered:
1) Aquisition of land ownership.
2) Interest during construction time.
3) Price escalation during construction time.

In tables 6 and 7, pages 43 and 44, the capital cost of the power station is tabulated. Below individual items will be discussed as far as is considered appropriate.

Items 1 and 2, wells and steam transmission pipes:

Wells are expected to be 1800 m deep, cased with 9 5/8" production casing and 7 5/8" slotted liner, extending to the bottom of the holes.

Drilling is planned with the "Gufubor" drill rig.

Estimated transportation cost of drilling equipment from Reykjavik to the thermal areas and back is 2 Mkr. Expected drilling cost of each well is, according to table 8 page 45, about 11.5 Mkr.

Estimated construction and erection cost of a separator at each well, together with a shelter and a damper for waste water, is 1.6 Mkr.

A separator at the station is estimated to cost 1.0 Mkr. Distance between wells is expected to be 100 m and the length of the steam mains transmission pipe as 200 m. The unit price of installed steam pipes in the network varies with the width and is estimated:

8"	-	6.500 Kr/m
10"	-	7.500 "
12"	-	8.500 "
14"	-	9.500 "

Item 3, turbine, generator, condenser:

On the basis of the results mentioned in section 2 tenders were obtained for three sizes of turbo-generators, 8, 12, and 16 MW with low or high level condenser.

The lowest tender was as follows:

	Low level condenser	High level condenser
8 MW	53 Mkr	55 Mkr
12 MW	66 "	69 "
16 MW	76 "	79 "

The figures are f.o.b. prices, thus transportation cost, insurance and installation cost will be added. It should be mentioned that the above tender amounts could possibly change somewhat in case of a bid as the bidding terms in general would be much more thoroughly defined, making the producers much more secure about the project.

Item 4, cooling tower and pumps:

On basis of the results mentioned in 1.2 and 2.4 tenders were obtained for the cooling tower and pumps. Special consideration was given to corrosion effects in selection of material. The tender amounts are f.o.b. prices:

	Cooling tower	Pumps
8 MW	8.4 Mkr	2.2 Mkr
12 MW	11.0 "	3.0 "
16 MW	14.9 "	3.7 "

Item 5, electrical system:

The design and cost estimate for the electrical system were prepared in cooperation with J. Indriðason, electrical engineer, who supplied the cost figures.

The estimate does not include the transmission line; just those parts of the electrical system within the power house and the switchgear annexe.

Item 6, power house, pump house:

The power house cost estimate was prepared by S. Thoroddsen and Partners, engineering consultants. Further information is to be found in their report. As stated in 2.7 the initially planned installation of the power house was altered, insulation augmented and the cost of sewers added etc., thus the cost figures of these items are not quite comparable to the abovementioned report. A cost estimate for a pump house is based on the unit prices for the power house.

Item 8, staff accommodation:

Five apartments are proposed to be built for permanent staff. The estimate is based on market price in the Reykjavík area, some deviations can therefore be expected.

Item 9, roads:

As discussed in 2,8 an access road connecting the Krafla thermal area to the inhabited region has to be constructed should that area be chosen. In the cost estimate the cheapest route, route 1 (see S. Thoroddsen and Partnes´s report, "Road to Víti") is expected to be the most suitable.

Items 10 and 11, unforeseen cost, engineering services and supervision:

As the engineering project in question is unparalleled in Iceland it is considered reasonable to estimate these items liberally, i.e. unforeseen cost is estimated as 15% of basic cost, but engineering serices as 10% of direct cost.

Table 6.

Initial cost

Geothermal power plant at Krafla/Námafjall

High-level condenser

Items		8MW	12MW	16MW
		Mkr	Mkr	Mkr
1.	Drill holes (4-4-5 holes)	48.0	48.0	59.5
2.	Steam transmission pipelines	14.2	14.2	16.6
3.	Turbine, generator, condenser	67.7	85.0	98.0
4.	Cooling tower, pumps, pipes for cooling water	19.8	26.1	34.2
5.	Electrical system	19.8	21.5	23.6
6.	Power house, pump house	25.4	29.1	32.8
7.	Cranes in power and pump houses	5.2	5.7	6.2
8.	Flats for staff	9.6	9.6	9.6
9.	Roads	7.0	7.0	7.0
	Basic cost	216.7	346.2	287.5
10.	Unforeseen cost 15%	32.5	36.9	43.1
	Direct cost	249.2	283.1	330.6
11.	Engineering and supervision 10%	24.9	28.3	33.0
	Initial cost	274.1	311.4	363.6

Table 7.

Initial cost

Geothermal power station at Krafla/Námafjall

Low-level condenser

Items		8MW	12MW	16MW
		Mkr	Mkr	Mkr
1.	Drillholes (4-4-5 holes)	48.0	48.0	59.5
2.	Steam transmission pipelines	14.0	14.2	16.6
3.	Turbine, generator, condenser	64.1	80.4	33.7
4.	Cooling tower, pumps, pipes for cooling water	19.8	26.1	34.2
5.	Electrical system	19.8	21.5	23.6
6.	Power house, pump house	28.5	33.3	38.1
7.	Cranes in power and pump houses	5.2	5.7	6.2
8.	Flats for staff	9.6	9.6	9.6
9.	Roads	7.0	7.0	7.0
	Basic cost	216.2	245.8	288.5
10.	Unforeseen cost 15%	32.4	36.9	43.3
	Direct cost	248.6	282.7	331.8
11.	Engineering and supervision 10%	24.9	38.3	33.2
	Initial cost	273.5	311.0	365.0

Table 8.

Cost of a well

			Unit price	Price kkr*	Total price kkr
1.	Material				4560
(1.1)	Casing 16"	30 m	4000	120	
(1.2)	" 13 3/8"	100 m	2760	276	
(1.3)	" 9 5/8"	300 m	1920	576	
(1.4)	" 7 5/8"	1300 m	1345	1748	
(1.5)	" 7 5/8"	200 m	2400	480	
(1.6)	Casing shoe			15	
(1.7)	Liner hanger			90	
(1.8)	Drill bits			560	
(1.9)	Well head			350	
(1.10)	Cement	100 tons	2.7	270	
(1.11)	Bentonite	75 sacks	1000	75	
2.	Bought service				820
(2.1)	Transportation			250	
(2.2)	Welding and workshop			300	
(2.3)	Transportation of drilling equipment			200	
(2.4)	Miscellaneous			70	
3.	Drilling platform				400
(3.1)	Cellar			150	
(3.2)	Earthwork			250	
4.	Time cost of drill rig				5360
(4.1)	Rental of drill	kr/day	89000		
(4.2)	Wages		28000		
(4.3)	Cars at well site	kr/day	5000		
(4.4)	Board and lodging of crew	kr/day	12000		
	40 work days	" "	134000		
5.	Percussion drillhole				300
			Total kkr.		11440

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* kkr = thousand Icelandic kronur.

4.2 Operating cost.

In tables 9 and 10, pages 51 and 52, the operating cost is subdivided and here below individual items will be discussed, as far as is considered necessary. On Fig. 21 energy cost is shown as a function of effective production time and size of power station.

Items 1,2 and 10, wells and steam transmission pipes.

It has hitherto been somewhat uncertain how the capital spent on steam wells should be repaid. The most common method used in this country as well as abroad is to depreciate them in 10 years and handle the capital expenses according to that on the basis of equal annual fees. This method can be somewhat misleading since wells as a profitable enterprise behave differently from those having a certain life span, after which they are either worthless or fully depreciated.

The steam output of a well must be expected to decrease gradually with time. Where the consumer's need for steam does not change additional wells have to be drilled at certain interwals to compensate for deterioration of wells.

As there is very limited experience in exploitation of geothermal steam in Iceland, there are still no figures to rely on as to how the steam output of a well decreases with time and information from abroad has been difficult to obtain. Thus, assumptions must primarily be relied on. The only available information from abroad is that in New-Zealand 3% of the capital cost of wells is intended annually for maintaining a constant quantity of steam. In Italy on the other hand a well is supposed to yield 40% of the initial steam output in 10 years time, but this figure is hardly comparable to circumstances in Iceland as in the above case the wells yield dry steam.

Below a proposition is made as to how the output capacity of wells decreases with time; the proposition accounts for four different alternatives, see Fig. 20, and coefficient b in equation 2.1 below is selected in accordance with that.

If four wells are assumed as a basis for steam aquisition and the pay-back period of capital set at <u>25 years</u> in accordance with other engineering projects, it can be computed from the curves at how long intervals a well has to be drilled to maintain a constant quantity of steam, and further how great a part of the capital cost of the first four wells has to be put into additional wells annually. It is also possible to calculate how many years this corresponds to in depreciation of the first four wells. It should be kept in mind that when the equation is treated in that way the additional wells are not considered as a property increase, but merely as maintenance for keeping the steam output constant.

The mathematical equation for the decrease in steam output according to Fig. 20 is:

$$M_t = M_o e^{-bt} \qquad (2.1)$$

where:

M_t : Steam quantity after t years
M_o : Steam quantity in unused well
e : 2.718
b : Coefficient 0.0958; 0.0719; 0.0575 and 0.0479
t : Time in years

The values selected for the coefficient b here require the drilling of one additional well at 3, 4, 5 and 6 years interval.

On the basis of this information it can be calculated how great a part of the capital cost of the first four wells need be estimated for the maintenance of the steam quantity with additional wells: at the same time the number of years it equals as depreciation of the first four wells can be computed.

This is done in the following way:

$$\text{Pr.val.} = 4A+A(1+r)^{-a}+A(1+r)^{-2a}+A(1+r)^{-an} \qquad (2.2)$$

Where:

Pr. val.: Present value of total expenses
A: Cost of each well
r: Interest rate 0.09
a: Years interval between additional wells
n: 1, 2, 3
a: Depreciation time of initial and additional wells 25 years.

From equation 2.2 can be deduced

$$(2.3) \quad \text{Pr.val.} = 4A+A\,\frac{(1+r)^{-a}((1+r)^{-an}\div 1)}{(1+r)^{-a}\div 1}$$

From this equation one can find the present value of the capital investment, which will be spent on the drilling of initial and additional wells during the next 25 years. Now the annual fee of this present value for the next 25 years can be found.

This annual fee is found according to the equation:

$$(2.4) \quad \text{Annual fee} = \text{Pr.val.}\frac{r}{(1-(1+r)^{-an})}$$

The annual fee can be divided into two parts, i.e. on one hand the annual fee for the pay-back of capital on initial wells in 25 years time and on the other the annual fee belonging to the pay-back of the capital spent on the drilling of additional wells.

Now the number of years needed for pay-back of the capital cost of the four first wells can also be found with the above annual fee, i.e. tha annual fee, which pays back the capital cost of the inital wells and additional wells in 25 years.

$$(2.5) \quad 4A = \text{Annual fee}\,\frac{1}{r}\,(1-(1+r)^{-c})$$

Here only the value r is unknown, but it indicates the number of years during which the capital cost 4A is payed back. This is the number of years usually referred to.

The results of the calculations are tabulated below:

Four initial wells. Depreciation time of initial wells 25 years.

Number of additional wells	Part of capital cost needed for drilling of additional wells annually	The equivalent number of years for pay-back of capital cost of four wells
1 well at 3 years interval	7.7%	9 years
1 " " 4 " "	5.5%	10 "
1 " " 5 " "	4.2%	11 "
1 " " 6 " "	3.4%	13 "

As the above table and Fig. 20 show the results are within the limits set by foreign results, as mentioned earlier.

In the present report the capital expenditure of wells is calculated on the basis of one additional well needed at four years interval, i.e. the first four wells ar depreciated in 25 years, but 5.5% of the capital cost of the first four wells is assumed annually for the drilling of additional wells

This method gives the same results as regards capital expenditure as the method usually applied so far, i.e. depreciating wells in 10 years.

Maintenance cost.

The maintenance of wells is commonly understood to include only those structures extending above ground, i.e. the uppermost part of casing and master valve.

Experience at Námafjall has shown that silicia precipitations are not to be expected in the wells, thus cleaning of the wells need not be considered.

The main components of separators and pipe network requiring maintainance, are valves, safety valves and expansion compensators.

It is considered fair to estimate the maintenance of wells as 1% of their capital cost and the maintenance of steam separators and pipe network as 1% of capital cost.

Items 3 - 8:

The pay-back period of capital cost is expected to be 25 years, which is a considerably shorter time than is usual as far as hydro power plants are concerned. Yet the circumstances, which are certainly considerably different, primarily the corrosion effect of sulphur-contaminated natural steam on certain parts of the engine and buildings, justify the assumption of a shorter lifetime of structures. Maintenance cost is estimated to be a fixed percentage of the capital cost of the relevant structure part. The percentage is generally higher here also than usually assumed for hydro power plants, the reasons being the same as stated above.

Staffing cost.

The power station is expected to be left unattended during night, thus inspection and maintenance duties will be carried out during two day shifts. The following operating staff is required for this work:

1 station manager
2 engineer
1 mechanic
1 electrician

Table 9.

Annual operating cost.

Geothermal power plant in Krafla/Námafjall areas.

Low level condenser

Items	8 MW Mkr	12 MW Mkr	16 MW Mkr
Capital cost (25 years, 8%):			
1. Wells	5,7	5,7	7,0
2. Steam transmission pipelines	1,6	1,6	1,9
3. Turbine, generator, condenser	7,6	9,5	11,1
4. Cooling tower, pumps, pipes for cooling water	2,4	3,0	4,0
5. Electrical system	2,4	2,5	2,7
6. Power house, pump house	3,4	3,9	4,5
7. Cranes for power and pump houses	0,6	0,6	0,7
8. Flats for staff	1,1	1,1	1,1
9. Roads	0,7	0,7	0,7
Maintenance cost:			
1. Wells (1%)*	0,6	0,6	0,7
2. Steam transmission pipelines (2%)	0,3	0,3	0,4
3. Turbine, generator, condenser (1.5%)	1,2	1,5	1,7
4. Cooling tower, pumps (1.5%)	0,4	0,5	0,6
5. Electrical system (1.5%)	0,4	0,4	0,5
6. Power house, pump house (0.14%)	0,1	0,1	0,1
7. Cranes for power and pump houses	0,1	0,1	0,1
8. Flats for staff (0.14%)	0,1	0,1	0,1
9. Roads (3%)	0,2	0,2	0,2
10. Additional wells (5.5%)	3,1	3,1	3,9
Other expenses:			
Cost of staff	3,0	3,0	3,0
Administration cost	0,5	0,5	0,5
Reserve funds	0.4	0.5	0.6
Operating cost	35.9	39,5	46,1

* % of capital cost

Table 10.

Annual operating cost.

Geothermal power plant in Krafla/Námafjall areas.

High level condenser

Items	8 MW Mkr	12 MW Mkr	16 MW Mkr
Capital cost (25 years, 8%):			
1. Wells	5,7	5,7	7,0
2. Steam transmission pipelines	1,6	1,6	1,9
3. Turbine, generator, condenser	8,0	10,1	11,6
4. Cooling tower, pumps, pipes for cooling water	2,4	3,0	4,0
5. Electrical system	2,4	2,5	2,7
6. Power house, pump house	3,0	3,4	3,8
7. Cranes for power and pump houses	0,6	0,6	0,7
8. Flats for staff	1,1	1,1	1,1
9. Roads	0,7	0,7	0,7
Maintenance cost:			
1. Wells (1%)[*]	0,6	0,6	0,7
2. Steam transmission pipelines (2%)	0,3	0,3	0,4
3. Turbine, generator, condenser (1.5%)	1,3	1,6	1,8
4. Cooling tower, pumps (1.5%)	0,4	0,5	0,6
5. Electrical system (1.5%)	0,4	0,4	0,5
6. Power house, pump house (0.14%)	0,1	0,1	0,1
7. Cranes for power and pump houses	0,1	0,1	0,1
8. Flats for staff (0.14%)	0,1	0,1	0,1
9. Roads (3%)	0,2	0,2	0,2
10. Additional wells (5.5%)	3,1	3,1	3,9
Other expenses:			
Cost of staff	3,0	3,0	3,0
Administration cost	0,5	0,5	0,5
Reserve funds	0,4	0,5	0,6
Operating cost	36,0	39,7	46,0

[*] % of capital cost

Glossary of some Icelandic words used in the Figures.

aðalloka = main valve
ára = years
borhola = drill hole (plural : borholur)
borun = drilling
borvídd = width of bore
dæla = pump
eimsvala þrýstingur = condensing pressure
eimsvali = condenser
en = but
eru = are
flansar = flanges
fóðringar = casings
fullt = complete
gufuleiðslur (-um) = steam pipes
gufumagn = quantity of steam
gufustreymi = steam flow
gufuþrýstingur = steam pressure
hitamælingu = temperature measurement
holutoppur = well head
högg borun = percussion drilling
kampprofilpakning = kampprofilegasket
kennilína = characteristic curve
kæliturn = cooling tower
með tímanum = with time
meðal borhola = "average well"
millibili = interval
orka = energy
orkukostnaður = energy cost
nýtingar tími = utilization time
rafall = generator
renniloki = gated valve
rýrnun = decrease
rör = casing
saman = together

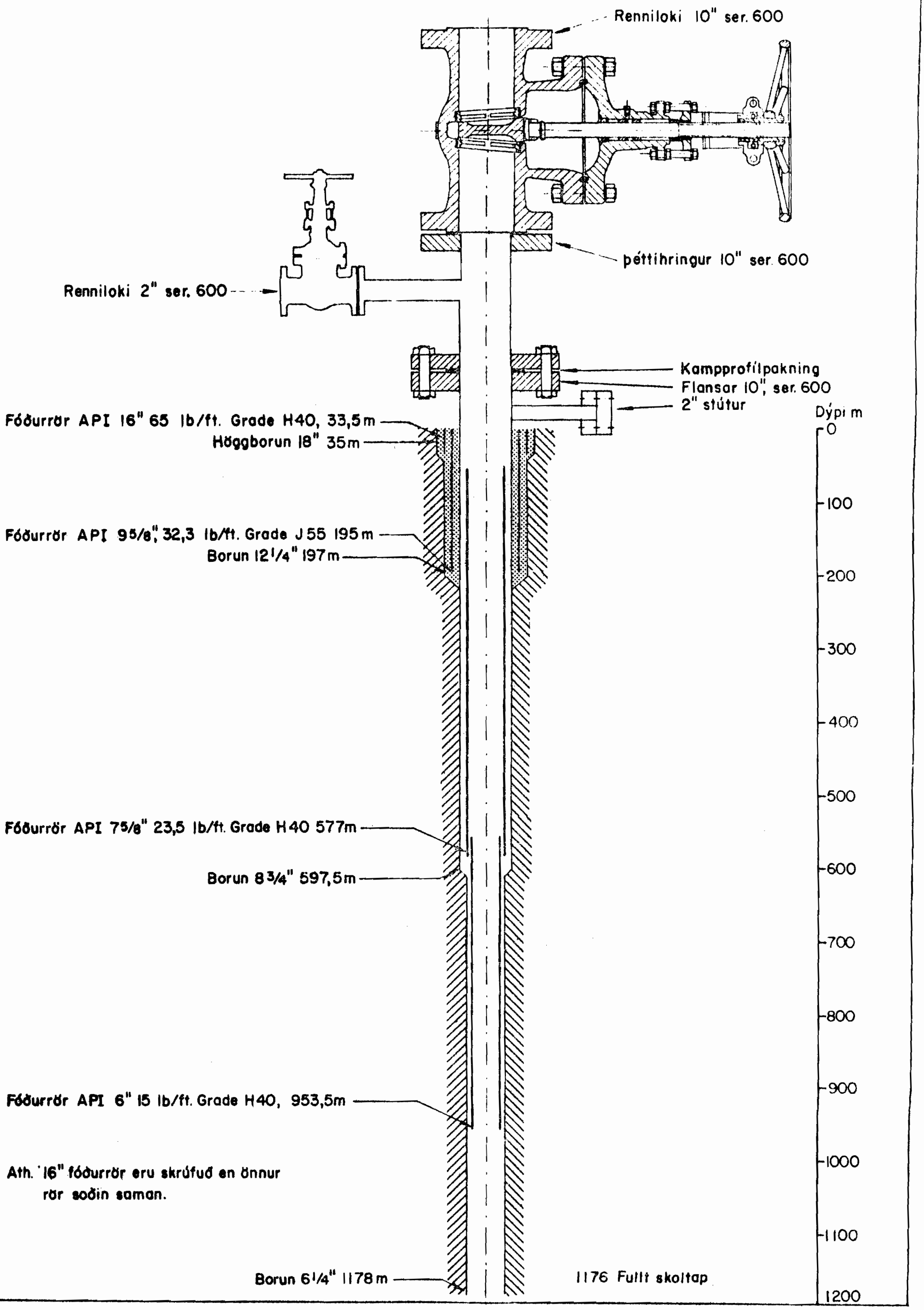
sjóðari = separator
skilja = separator
skoltap = circulation loss
skrúfuð = screwed
skv. = according to
soðin = welded
stofn holur = initial wells
stútur = tap
túrbína = turbine
úr = from
varmafall = heat loss
við breytilegan = at varying
viðhalds hola = additional well
þéttihringur = seal ring
þrýstingur = pressure
æð = aquifer
önnur = but

ORKUSTOFNUN
Jarðhitadeild

Bornola 6, Námafjalli
Borvídd, fóðringar og holutoppur

31.1.'72 BE/EK.
Tnr. 136
J-Námafjall
Fnr. 10400

Mynd 1



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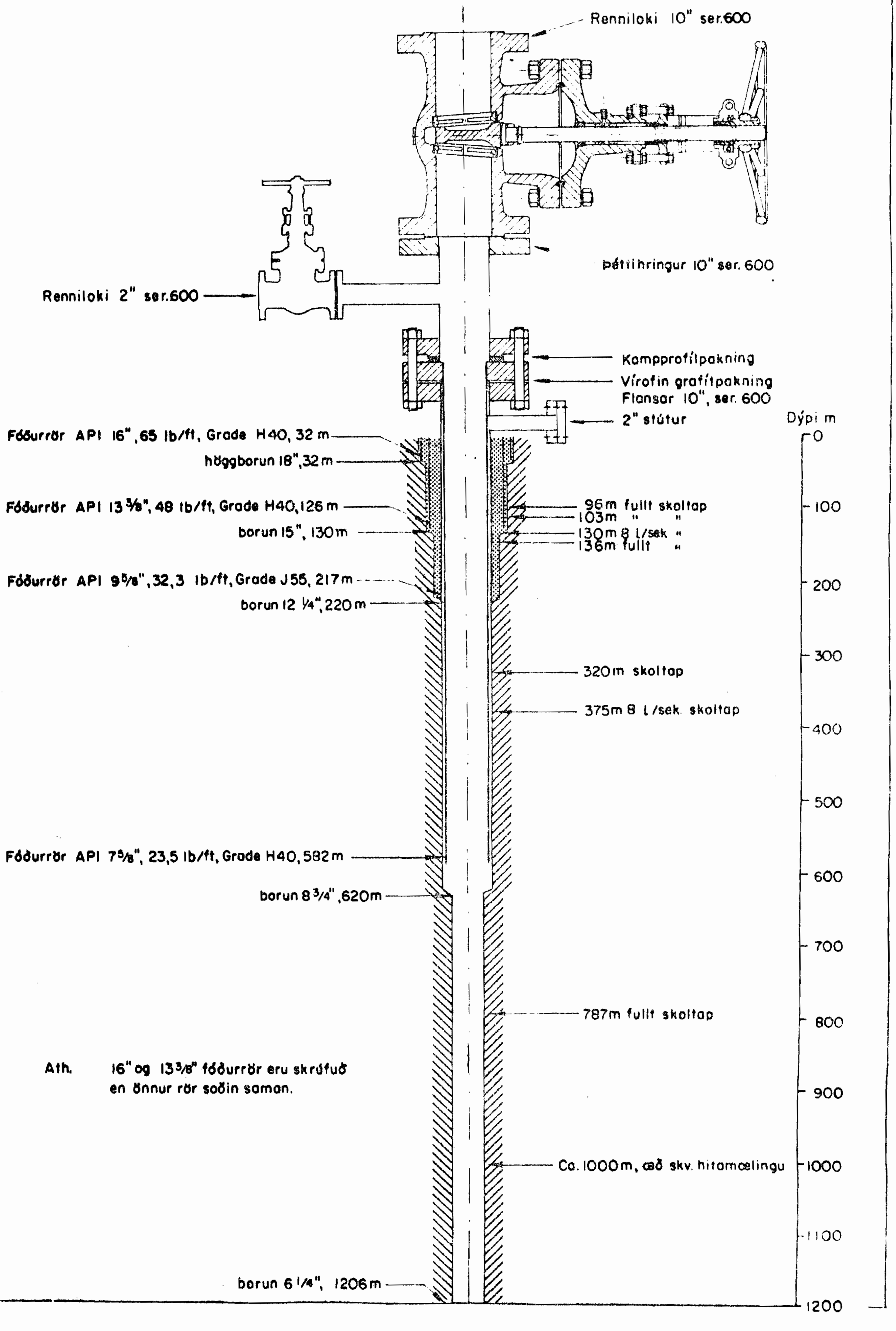
Borvídd, fóðringar og holutoppur

17.11.'71 KR/EK
Tnr. 130 Tnr. 293
J-Námafj. J-Ým.
Fnr. 10319

Mynd 2



Ath. 16" og 13 3/8" fóðurrör eru skrúfuð en önnur rör soðin saman.

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Borhola 8, Námafjalli
Borvídd, fóðringar og holutoppur

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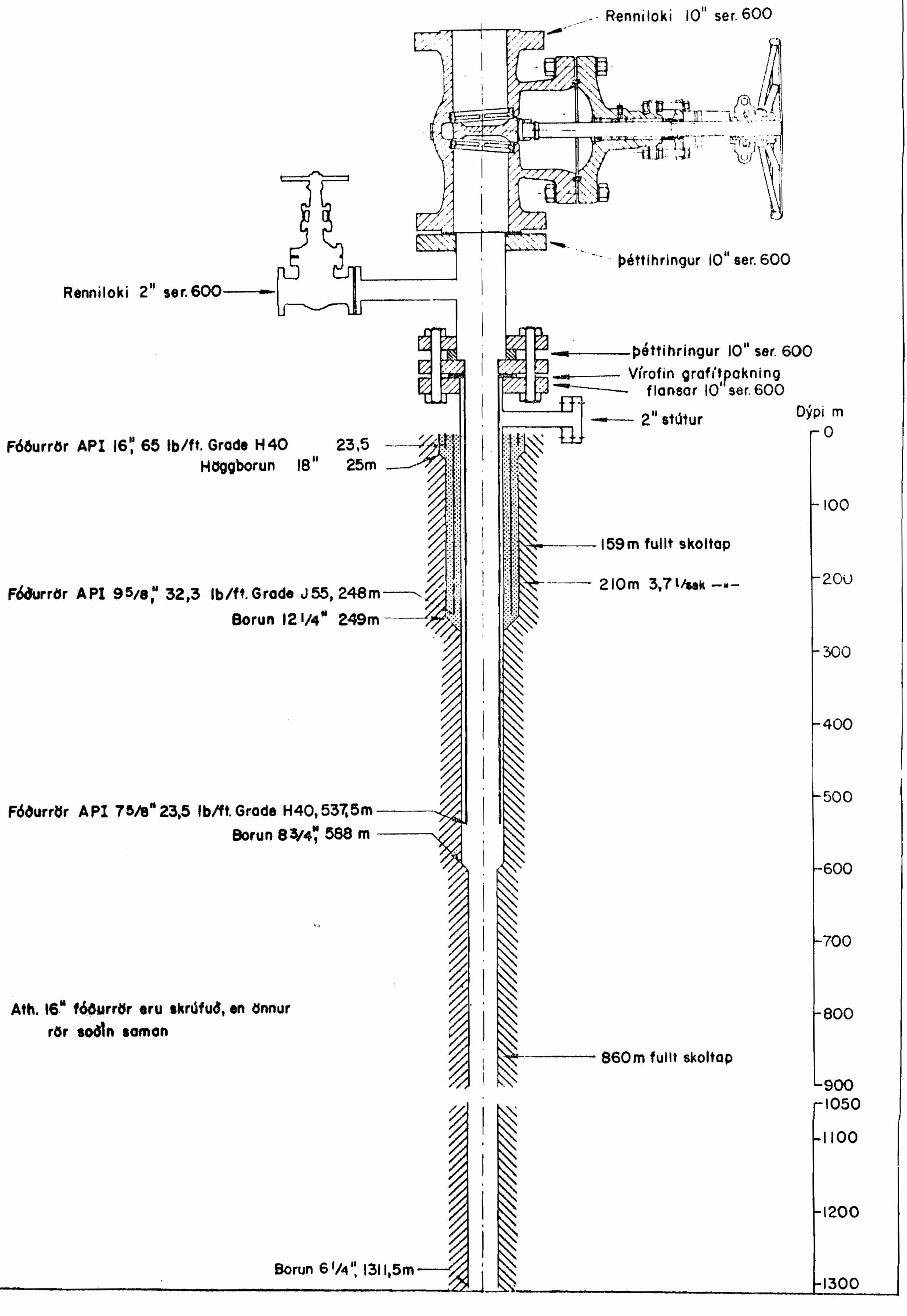
Tnr. 137
J-Námafjall
Fnr. 10401

Mynd 3



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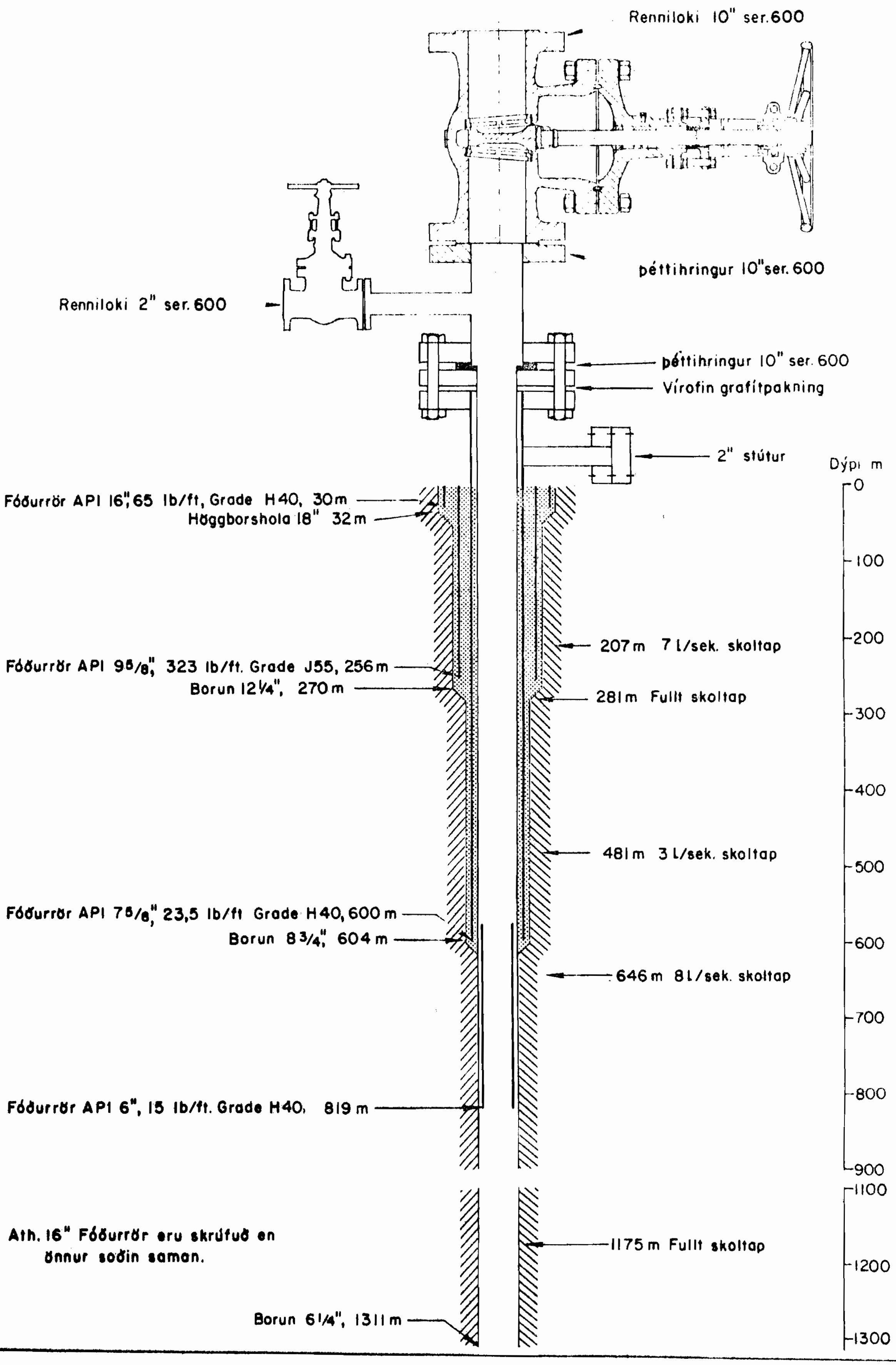
Borhola 9 Námafjalli
Borvídd, fóðringar og holutoppur.

25.2.'72 BE/EK.
Tnr. 138
J - Námafjalli
Fnr. 10426

Mynd 4



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Jarðhitadeild

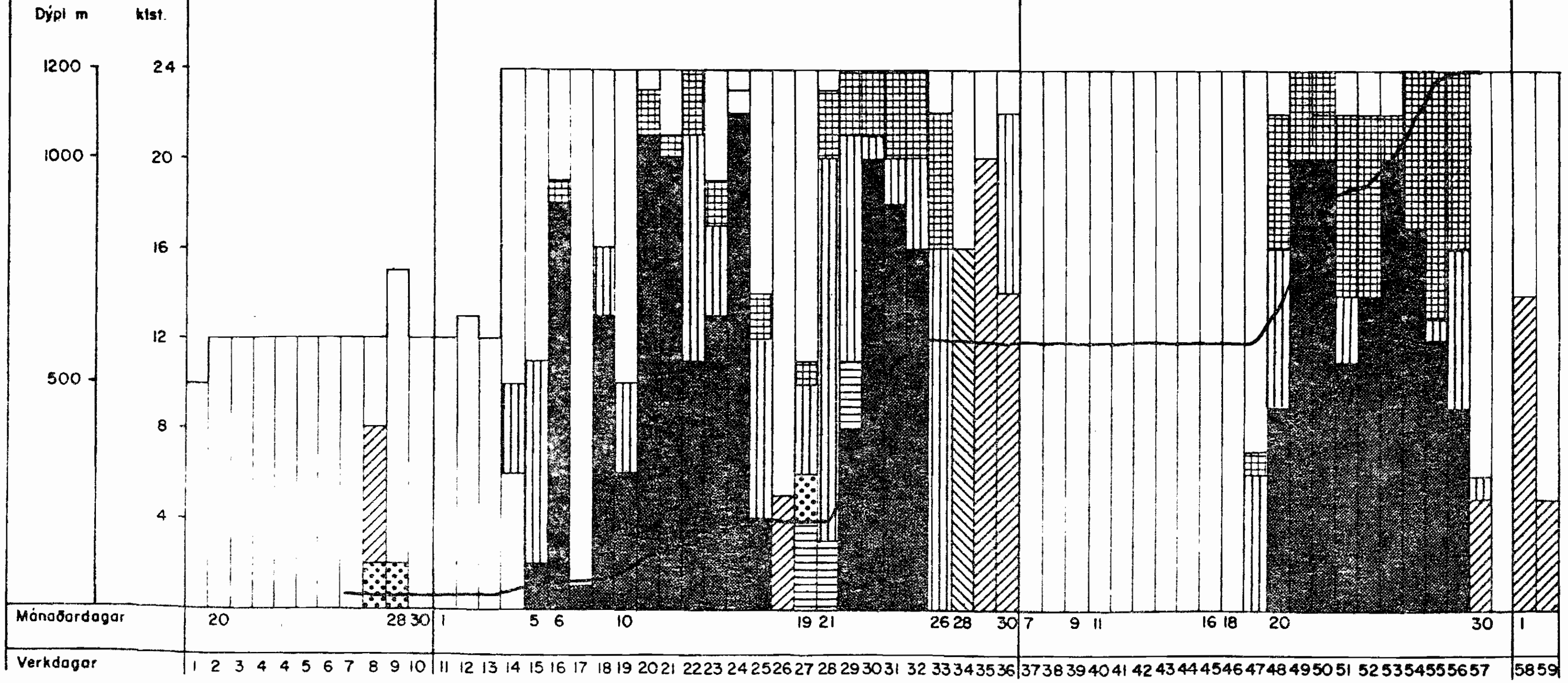
JARÐVARMAVEITUR RÍKISINS
BORUN NORÐURBORS
Hola 6, Námafjalli

11.2.'72 BE/eó
Tnr. 134
J-Námafjall
Fnr. 10379

	VERKHLUTAR	Júní 1969										
		19	20	21	22	23	24	25	26	27	28	30
▓	1. Borun á botni											
☰	2. Boruð steypu											
⁘	3. Steyping									2	2	
▧	4. Víkkun											
▨	5. Fóðrun									6		
▥	6. Trygging Holu											
▦	7. Borkrónuskipti											
	8 Flutn. undirbún.	10	12	5		12	6	4	4	2	7	10
	9. Ferðir, að og frá											
	10 Tafir. Fisk.											
	11 Biðtímar			7			6	8	8	2	6	2
	12 Viðgerðir											
	13 Ferðalög											
	14 Annað											

VERKHLUTAR	Júlí																									
	1	2	3	4	5	7	8	9	10	11	12	14	15	16	17	18	19	21	22	23	24	25	26	28	29	30
1. Borun á botni				6	2	18	1	13	6	21	20	11	13	22	4				8	20	18	16				
2. Boruð steypu																		3	3							
3. Steyping																	2									
4. Víkkun																								16		
5. Fóðrun																5									20	14
6. Trygging Holu				4	9			3	4			10	4		8		4	18	10	1	2	4	16			8
7. Borkrónuskipti						1				2	1	3	2	1	2		1	2	3	3	4	4	6			
8 Flutn. undirbún.	10	9	10	6											3	8								1	4	
9. Ferðir, að og frá																										
10 Tafir. Fisk.																										
11 Biðtímar	2	4	2	8	13	5	23	8	14	1	3		5	1	7	11	13							1		
12 Viðgerðir																										
13 Ferðalög																										
14 Annað																		1					2			2

VERKHLUTAR	Ágúst																						Sept.		Alls		
	7	8	9	11	12	13	14	15	16	18	19	20	21	22	23	25	26	27	28	29	30	31	1	2	klst.	%	%
1. Borun á botni												9	20	20	11	19	20	17	12	9					331	29.1	
2. Boruð steypu																									10	0.9	
3. Steyping																									6	0.5	
4. Víkkun																									16	1.4	
5. Fóðrun																					5		14	5	69	6.0	
6. Trygging Holu											6	7	1	2	3			1	1	8					135	11.8	
7. Borkrónuskipti											1	6	3	2	8	8	2	6	11	7					89	7.8	575
8 Flutn. undirbún.											12	2			2	1					18		10	19	193	16.2	
9. Ferðir, að og frá																											
10 Tafir. Fisk.	12	12	12				12	12	12	6															78	6.8	
11 Biðtímar				12	12	12				6	5					1	2								210	18.4	
12 Viðgerðir																											
13 Ferðalög																											
14 Annað																									5	0.4	42.5
																									142	100.0	100



Mynd 5

ORKUSTOFNUN
Jarðhitadeild

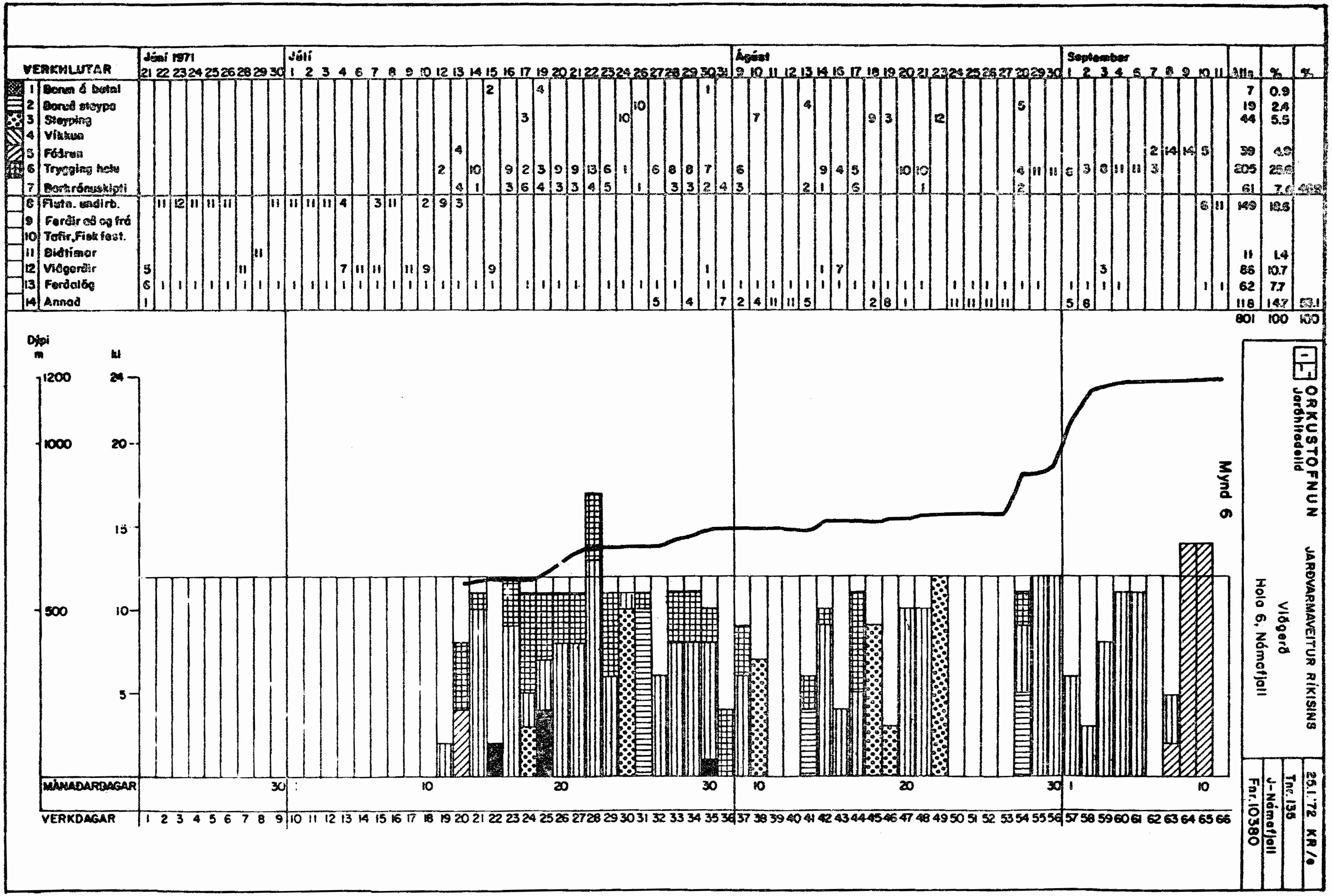
JARÐVARMAVEITUR RÍKISINS

Viðgerð

Hola 6, Námafjall

25.1.'72 KR/e
Tnr. 135
J-Námafjall
Fnr. 10380

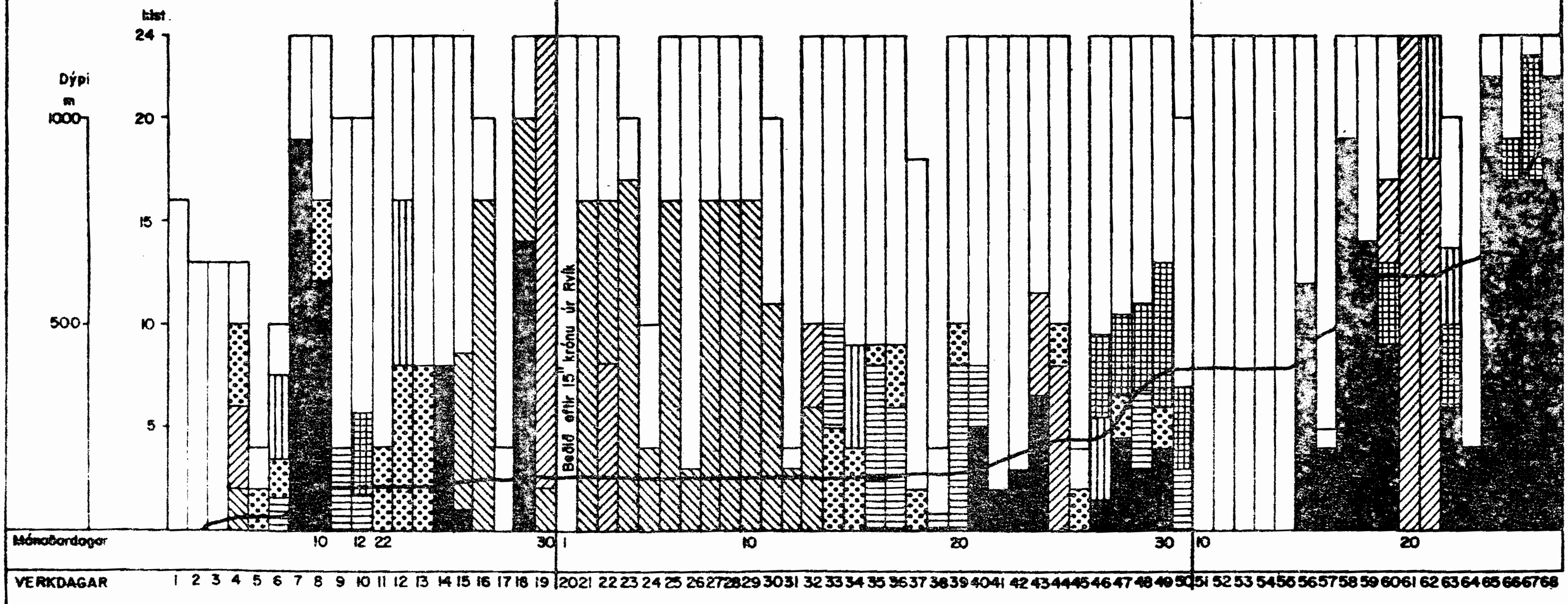
Mynd 6



		VERKHLUTAR	September																		
			3	4	5	6	7	8	9	10	11	12	22	23	24	25	26	27	28	29	30
▓	1	Borun á botni							19	12						8	1			12	
▥	2	Boruð steypa						2			4	12									
░	3	Steyping				4	2	2		4			4	8	8						
▨	4	Víkkun				2											8	16		8	2
▧	5	Fóðrun				4															22
▤	6	Trygging holu						4						8							
▦	7	Borkrónuskipti										4									
	8	Flutn. undirb.	16	13	13																
	9	Ferðir að og frá																			
	10	Tafir fizk. fesk.								3											
	11	Biðtími				3				2	16	10	16	8	8	8	8				
	12	Viðgerðir											4		4	1					
	13	Ferðalög																			
	14	Annað					2	2	5	3	4	4			4	7	7	4	4	4	
	15.	Borkrónur	0					1								2	0				

		VERKHLUTAR	Október																														
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
▓	1	Borun á botni																					5	2	3	7			2	5	3	4	
▥	2	Boruð steypa														5		8	6		1	8	3								4		3
░	3	Steyping														5	4	1	3	2		8					2	2		2		2	2
▨	4	Víkkun		16	8	16	4	16	3	16	16	16	11	3	6																		
▧	5	Fóðrun			8										4											5	8						
▤	6	Trygging holu															5												4				
▦	7	Borkrónuskipti																											4	4	4	8	4
	8	Flutn. undirb.																															
	9	Ferðir að og frá																															
	10	Tafir fizk. fesk.																	2														
	11	Biðtími	24		8				13	6							6	15		4		8	8	6	2		4			4	13	10	4
	12	Viðgerðir				1																		12	13								
	13	Ferðalög																															
	14	Annað		8		3	6	8	8	2	8	8	8	1	14	14	9		13	12	3		8			12	10	2	14	9			7
	15.	Borkrónur		x												3													4				

		VERKHLUTAR	Nóvember																		Alls	%	%
			10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27			
▓	1	Borun á botni						12	4	19	14	9			6	4	22	17	17	22	229	16.4	
▥	2	Boruð steypa																			46	3.3	
░	3	Steyping																			65	4.7	
▨	4	Víkkun																			170	12.2	
▧	5	Fóðrun										4	24	18							87	7.0	
▤	6	Trygging holu					24	12						6	4						67	4.8	
▦	7	Borkrónuskipti										4			4			2	6		44	3.2	51.6
	8	Flutn. undirb.				24															66	4.7	
	9	Ferðir að og frá																			60	4.3	
	10	Tafir fizk. fesk.																			5	0.4	
	11	Biðtími																			214	15.4	
	12	Viðgerðir								1											42	3.0	
	13	Ferðalög																					
	14	Annað			12				1	4	10	7			6	1	2	5	1	2	286	20.6	43.4
	15.	Borkrónur													5				6		391	100.0	



ORKUSTOFNUN
Jarðhitadeild

JARÐVARMAVEITUR RÍKISINS

BORUN NORÐURBORS
Hola 7, Námafjalli

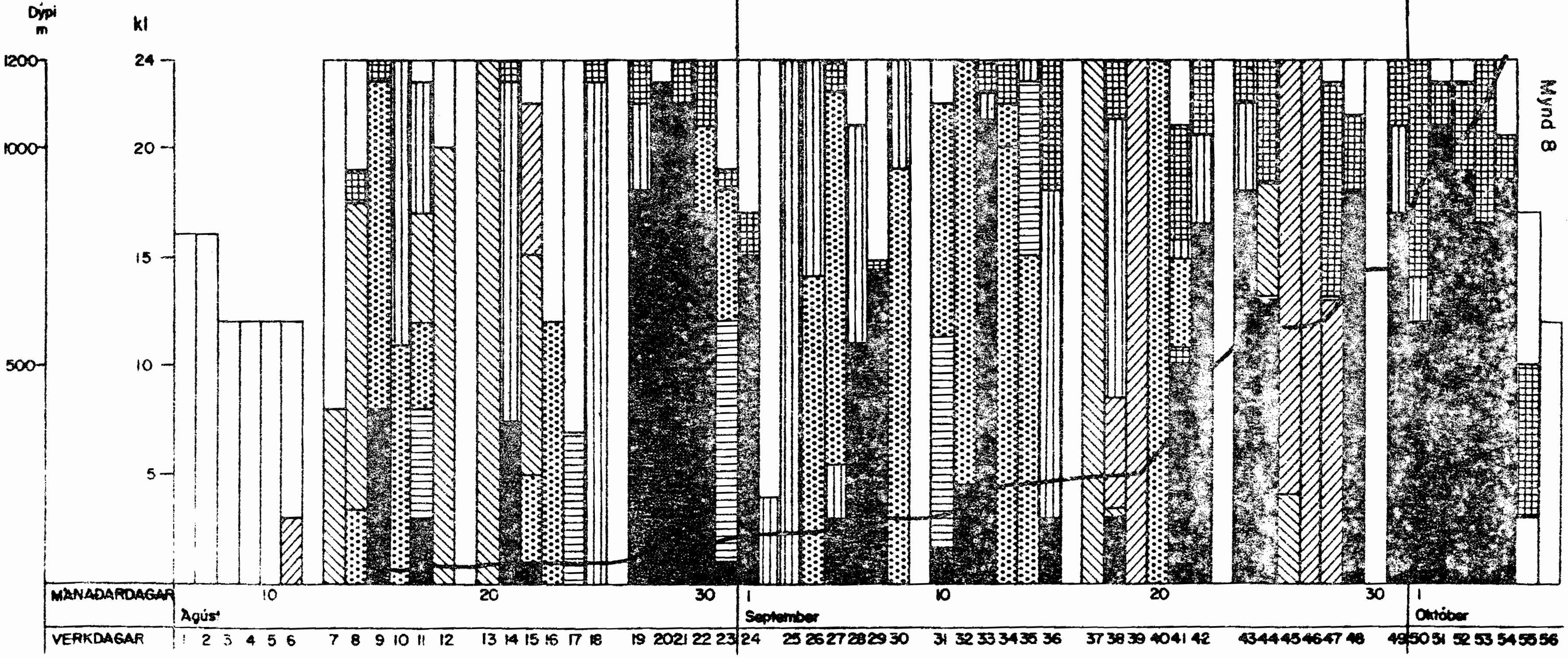
22.2.'72 BE/ed
Tnr. 133
J-Námaskarð
Fnr. 10363

Mynd 7

		VERKHLUTAR	Ágúst 1970																									
			6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
▓	1	Borun á botni										8		3				7.5	1					18	23	22	17	1
▤	2	Boruð steypa												5							7							11
░	3	Steyping									3.5	15	11	4					4	12							4	6
▧	4	Víkkun								8	14			5	20		24		10									
▨	5	Fóðrun						3											7									
▥	6	Trygging holu											13	6				15.5				23		4				
▦	7	Borkz. skipti									1.5	1						1				1		2		2	3	1
☐	8	Flutn.-undirb.	16	16	12	12	12	9		16										12	17							
☐	9	Ferðin að og frá																										
☐	10	Tafir, Fisk. fest									5																	
☐	11	Biðtímar																	2						1			5
☐	12	Viðgerðir												1	4													
☐	13	Ferðalög																										
☐	14	Annað																										

		VERKHLUTAR	September																														
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
▓	1	Borun á botni	15				3	11	14.2			1.7	10.5	21.2			3			3			10.2	14.5		18	13.2			1	18		17
▤	2	Boruð steypa					2.5					10	13.5			8							1										
░	3	Steyping				14	17			19		10.3			22	15						24	4										
▧	4	Víkkun																	24	0.5							5	4					
▨	5	Fóðrun																		5	24							20	24	12			
▥	6	Trygging holu		4	24	10		10		5				1.3		1	15			13			0.8	4		4							4
▦	7	Borkz. skipti	2				1.5		0.5			2		1.5	2		6			2.5			5	5.5		2	5.8			10	3.5		3
☐	8	Flutn.-undirb.																															
☐	9	Ferðin að og frá																															
☐	10	Tafir, Fisk. fest																															
☐	11	Biðtímar	7						9.3																								
☐	12	Viðgerðir						3															3							1	2.5		
☐	13	Ferðalög																															
☐	14	Annað																															

		VERKHLUTAR	Október							Alls	%	%
			1	2	3	4	5	6	7			
▓	1	Borun á botni	12	21	19	16.7	18.5	3		361	28,5	
▤	2	Boruð steypa								64	5.0	
░	3	Steyping								185	14.8	
▧	4	Víkkun								114	9.0	
▨	5	Fóðrun								95	7.5	
▥	6	Trygging holu	2							160	12.6	
▦	7	Borkz. skipti	10	2	4	7.3	2	7		96	7.6	85
☐	8	Flutn.-undirb.						7	12	141	11.2	
☐	9	Ferðin að og frá										
☐	10	Tafir, Fisk. fest								5	0.4	
☐	11	Biðtímar								23	1.8	
☐	12	Viðgerðir		1	1		3.5			20	1.6	
☐	13	Ferðalög										
☐	14	Annað										15
										1264	100	100



Mynd 8

ORKUSTOFNUN
Jarðhitadeild

JAÐVARMAVEITUR RÍKISINS

BORUN NORÐURBORS
Hola 8.Námafjalli

5.12.'71 KR/eó
Tnr. 131
J-Námafjall
Fnr. 10338

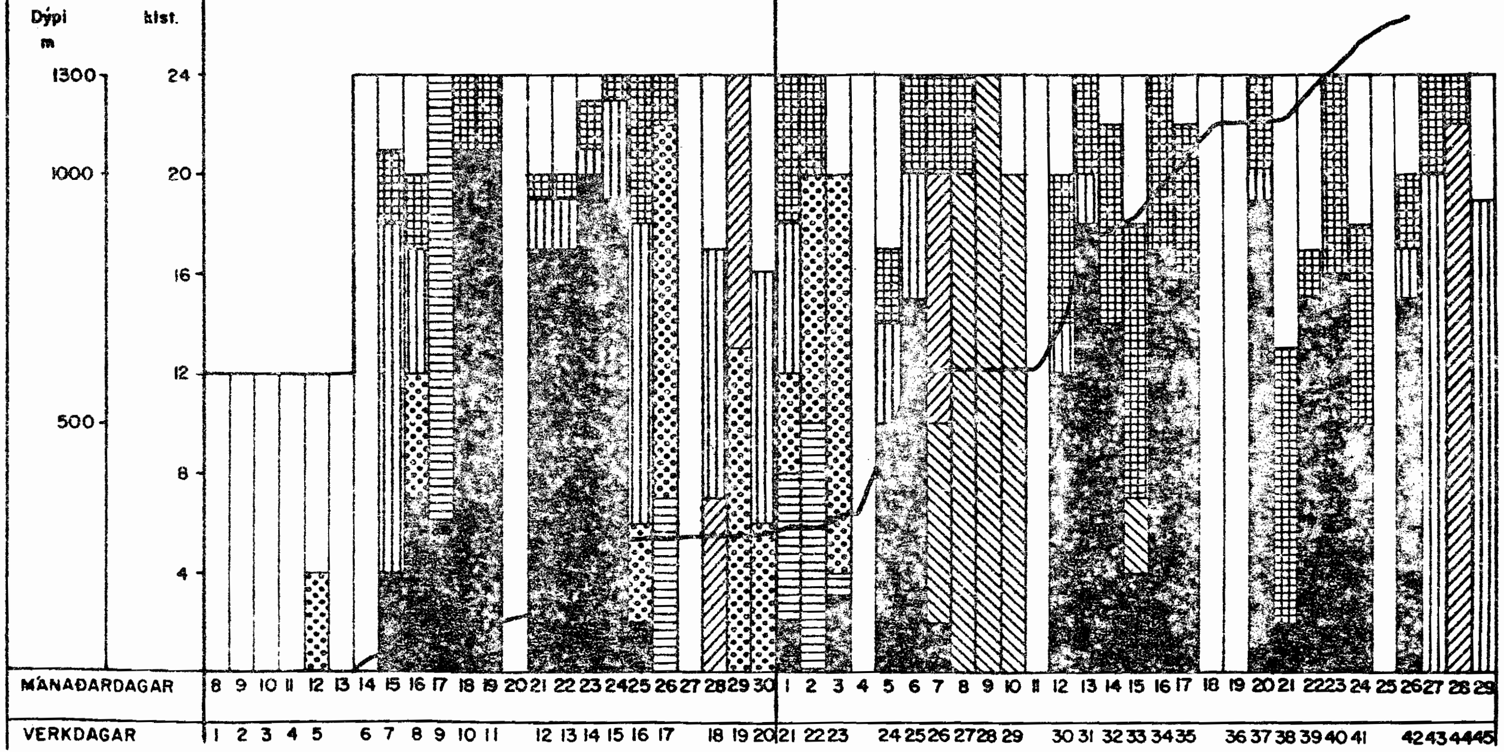
ORKUSTOFNUN
Jarðhitadeild

JARÐVARMAVEITUR RÍKISINS

BORUN NORÐUBORS
Hola 9, Námafjalli

10.12'71 BE/EÓ
Tnr. 132
J - Námafjall
Fnr. 10362

			Október 1970																							September																															
		VERKHLUTAR	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	Alls	%	%
▓	1	Borun á botni								4	7	6	21	21		17	17	20	19	2						2		3		10	15	2					12	18	14	4	17	16			19	2	15	16	10		15				324	31,8	
▤	2	Boruð steypa										18									7					6	10	1																											42	4,1	
⁘	3	Steyping					4				5									4	15			13	6	4	10	16																											77	7,5	
▧	4	Víkkun																														8								3															11	1,1	
▨	5	Fóðrun																					7	11								10	20	24	20																		22		114	11,2	
▥	6	Trygging holu								14	5			1		2	2	1	4	12			10		10	6				4	5						2	2							1						2	20		19	122	12,0	
▦	7	Borkrónuskipti								3	3		3	2		1	1	2	1	6	2					6	4			3	4	4	4				6	4	8	11	7	6			4	11	2	8	8		3	4	2		133	13,0	80,7
☐	8	Flutn. undirb.	12	12	12	12	8		24														7		8			4		7												2		12							4			3	129	12.6	
☐	9	Tafir Fisk.																																						6															6	06	
☐	10	Biðtímar																																																							
☐	11	Viðgerðir								3	4					4	4	1																	4		4		2					12		11	7		6						62	6.1	
☐	12	Ferðir að og frá																																																							
☐	13	Forðalög																																																							
☐	14	Annað																																																							19.3
																																																							1020	100	



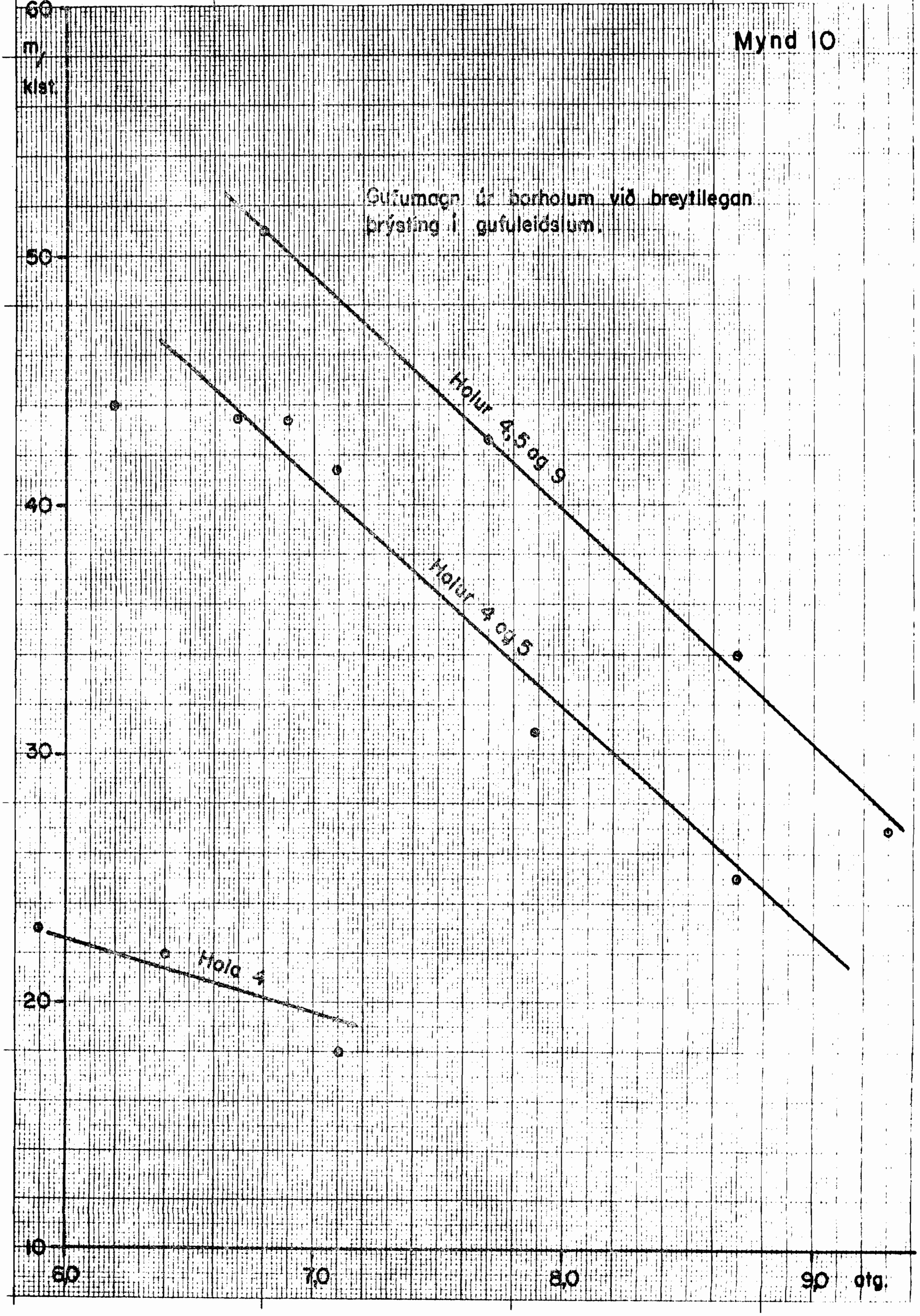
Mynd 9

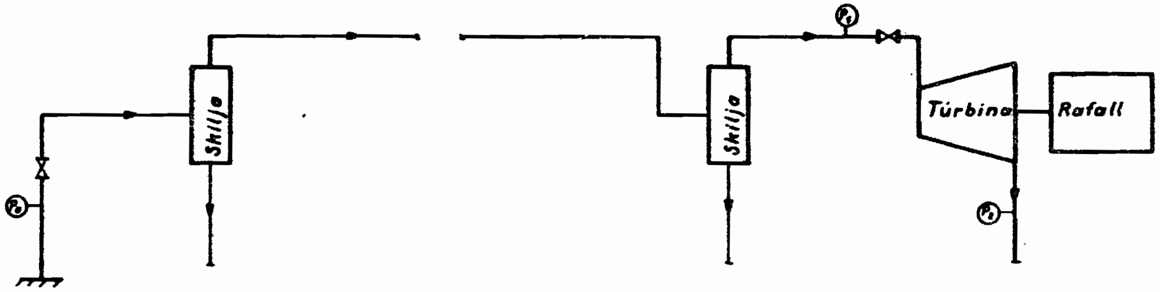
ORKUSTOFNUN
Jarðhitadeild

Kennilína borhola 4,5 og 9 í Námafjalli

12.2.'71 KR / P
Tnr. 94
J - Námafj.
Fnr. 9766

Mynd 10





Mynd II

Fl.	Heiti	Hl.nr.	Teikn. nr.	Efni	Aths.

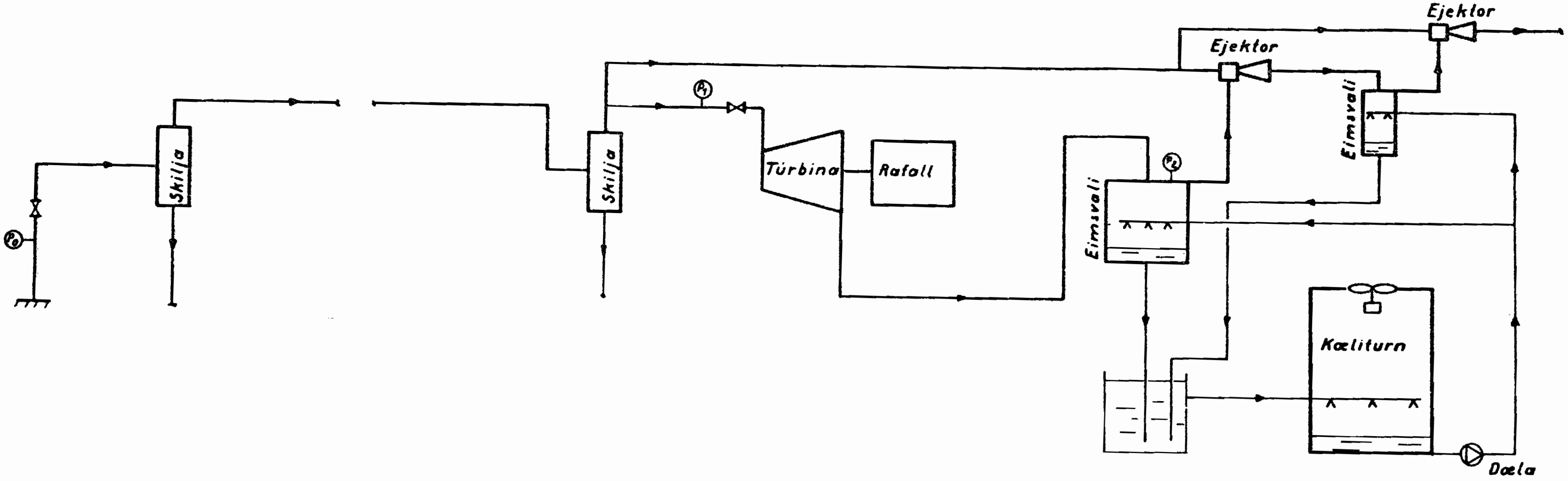
Breyting	Dags.	Leiðrétting	Dags.	Leiðrétting

VERKFÆÐISTOFA GUÐMUNDAR & KRISTJÁNS
Skólavörðustíg 3a
Sími 14425

Mkv.			
⁒	Verkf.	4.'71	JM
	Teikn.		
	Yfirf.		
	Samþ.		

Orkustofnun
Gufuaflstöð við Kröflu
Kerfi 1, Mótþrýstivél

Dagbók nr.
TEIKNING NR.
K-2-12
Verk nr. blað af



Mynd 12

Fl	Heiti	Hl.nr.	Teikn. nr.	Efni	Aths.

Breyting	Dags.	Leiðrétting	Dags.	Leiðrétting

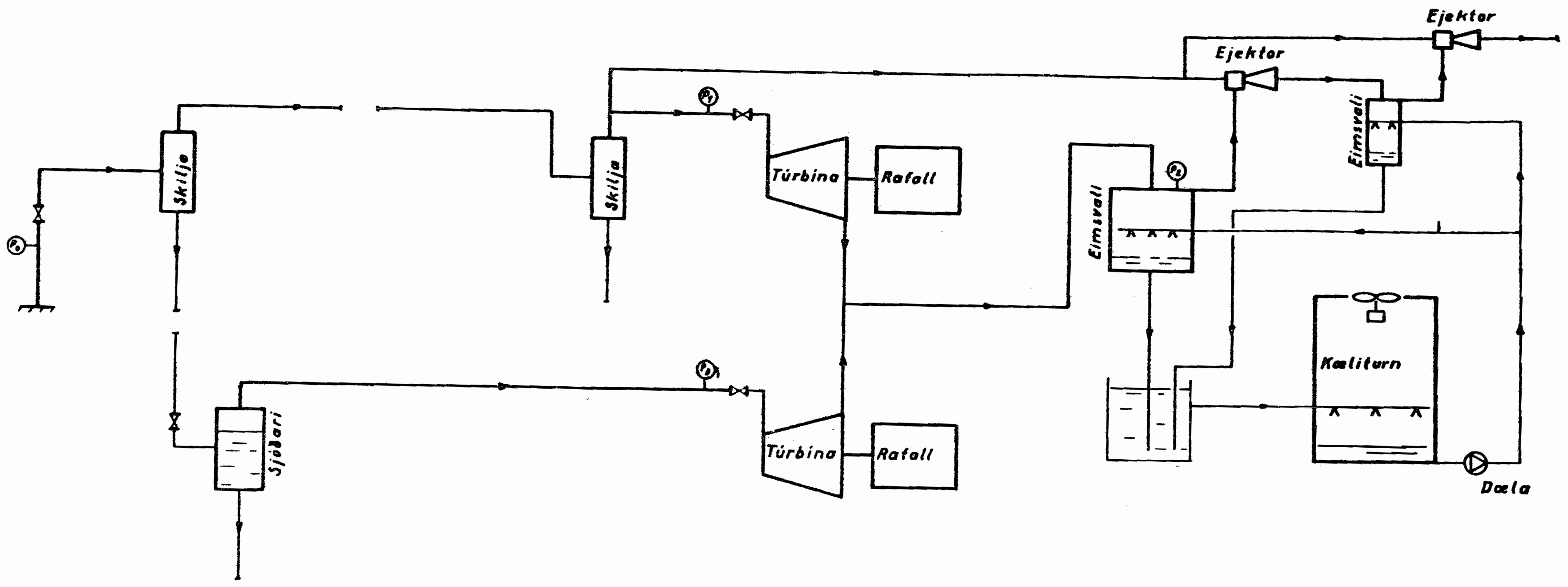
VERKFÆÐISTOFA GUÐMUNDAR & KRISTJÁNS

Skólavörðustig 3a Sími 14425

Mkv.			
⁄.	Verkf.	4.'71	JM
	Teikn.		
	Yfirf.		
	Samþ.		

Orkustofnun
Gufuaflstöð við Kröflu
Kerfi 2, Eimsvalavél
Borholuvatn ónotað

Dagbók nr.
TEIKNING NR.
K-2-13



Mynd 13

Fj.	Heiti	Hl.nr.	Teikn. nr.	Efni	Athс.

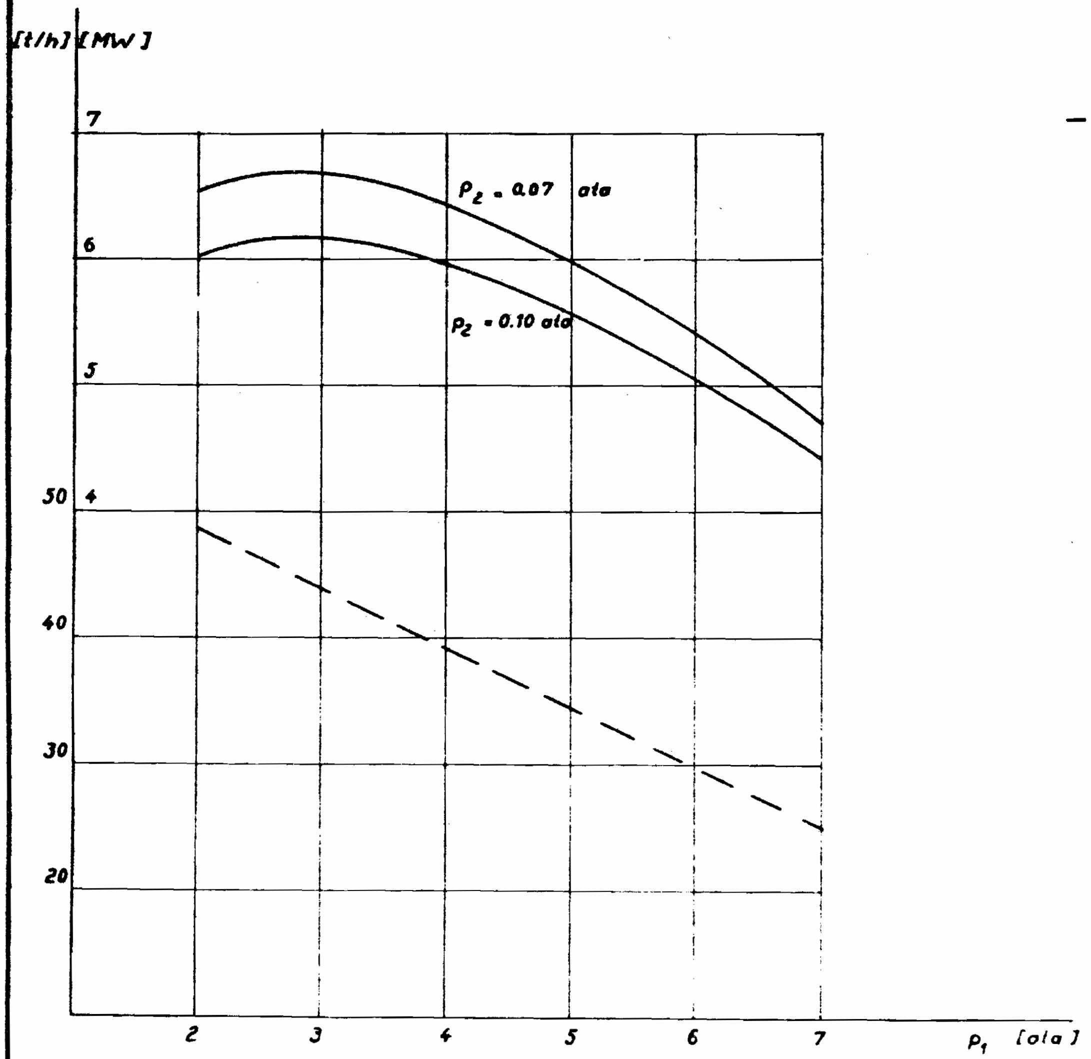
Breyting	Dags.	Leiðrétting	Dags.	Leiðrétting

VERKFÆÐISTOFA GUÐMUNDAR & KRISTJÁNS
Skólavörðustig 3a Sími 14425

Mkv.			
⁄.	Verkf.	4.'71	JM
	Teikn.		
	Yfirf.		
	Samþ.		

Orkustofnun
Gufuaflstöð við Kröflu
Kerfi 3 . Eimsvalavélar
Borholuvatn notað

Dagbók nr.
TEIKNING NR.
K - 2 - 14
Verk nr. blað af



——— Orka borholu við isentrop varmafall í túrbínu.

— — — Gufustreymi úr meðalborholu.

p_1 Gufuþrýstingur við aðalloka túrbínu.

p_2 Eimsvalaþrýstingur.

Mynd 14

Fl.	Heiti	Hl.nr.	Teikn. nr.	Efni	Aths.

Breyting

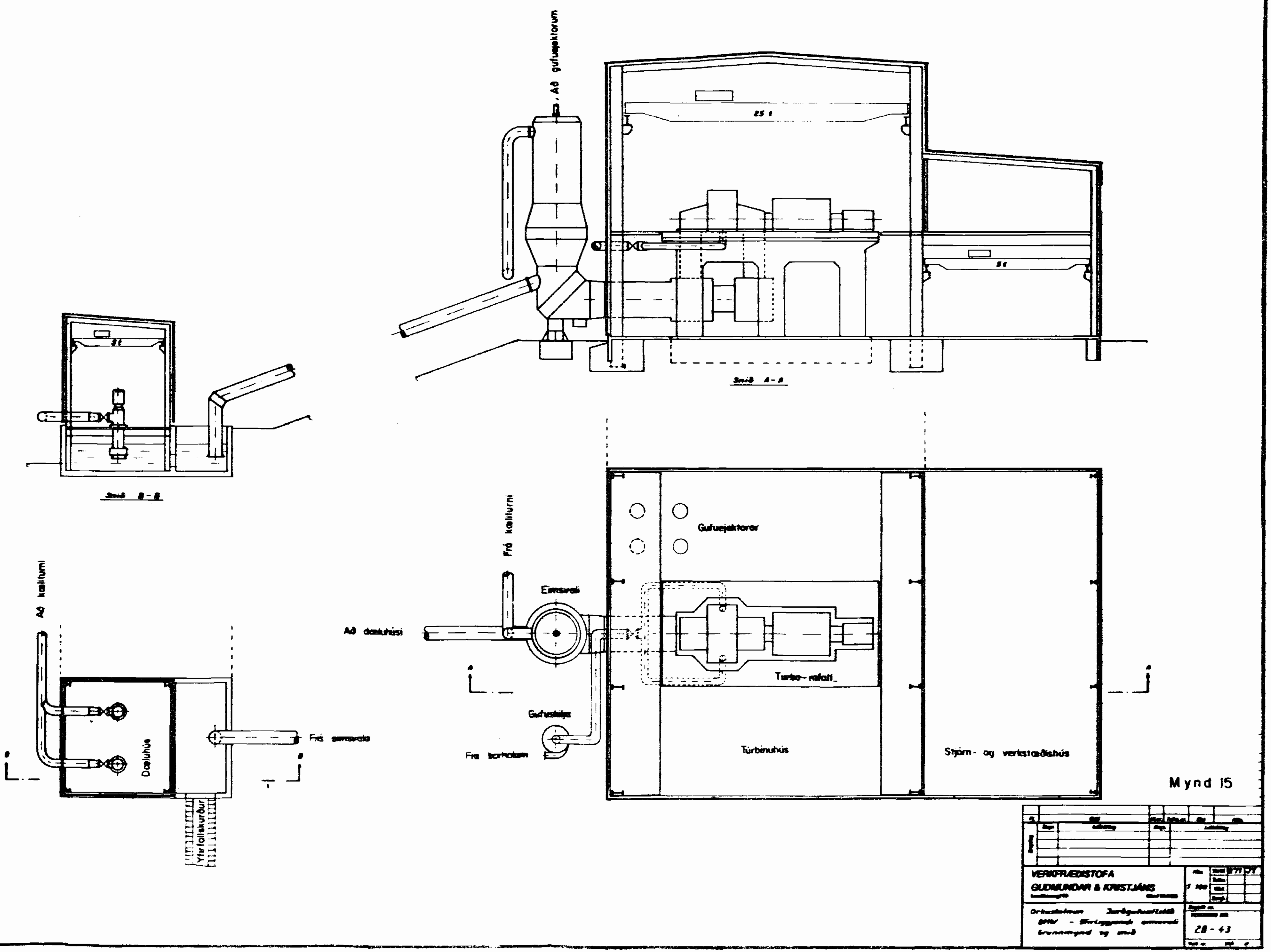
Dags.	Leiðrétting	Dags.	Leiðrétting

VERKFRÆÐISTOFA GUÐMUNDAR & KRISTJÁNS
Skólavörðustíg 3a Sími 14425

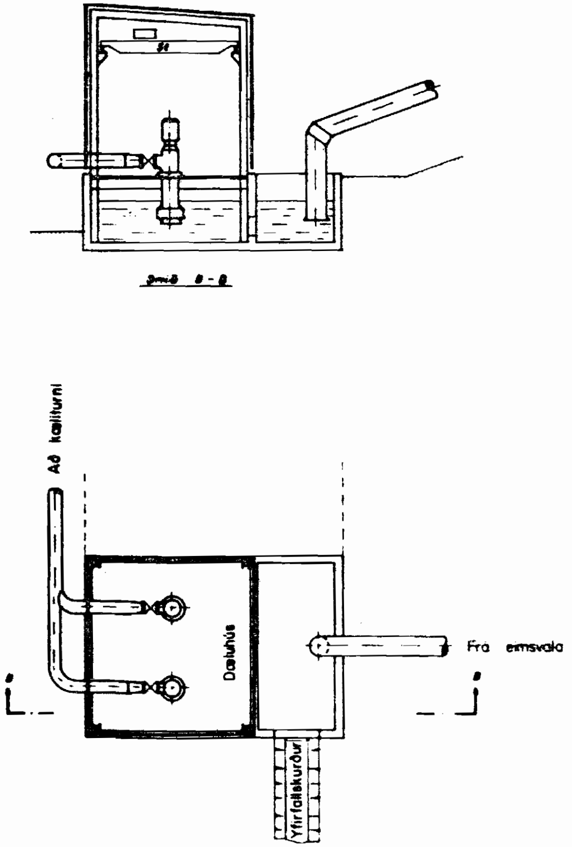
Mkv.
Verkf. 4.'71 JM
Teikn.
Yfirf.
Samþ.

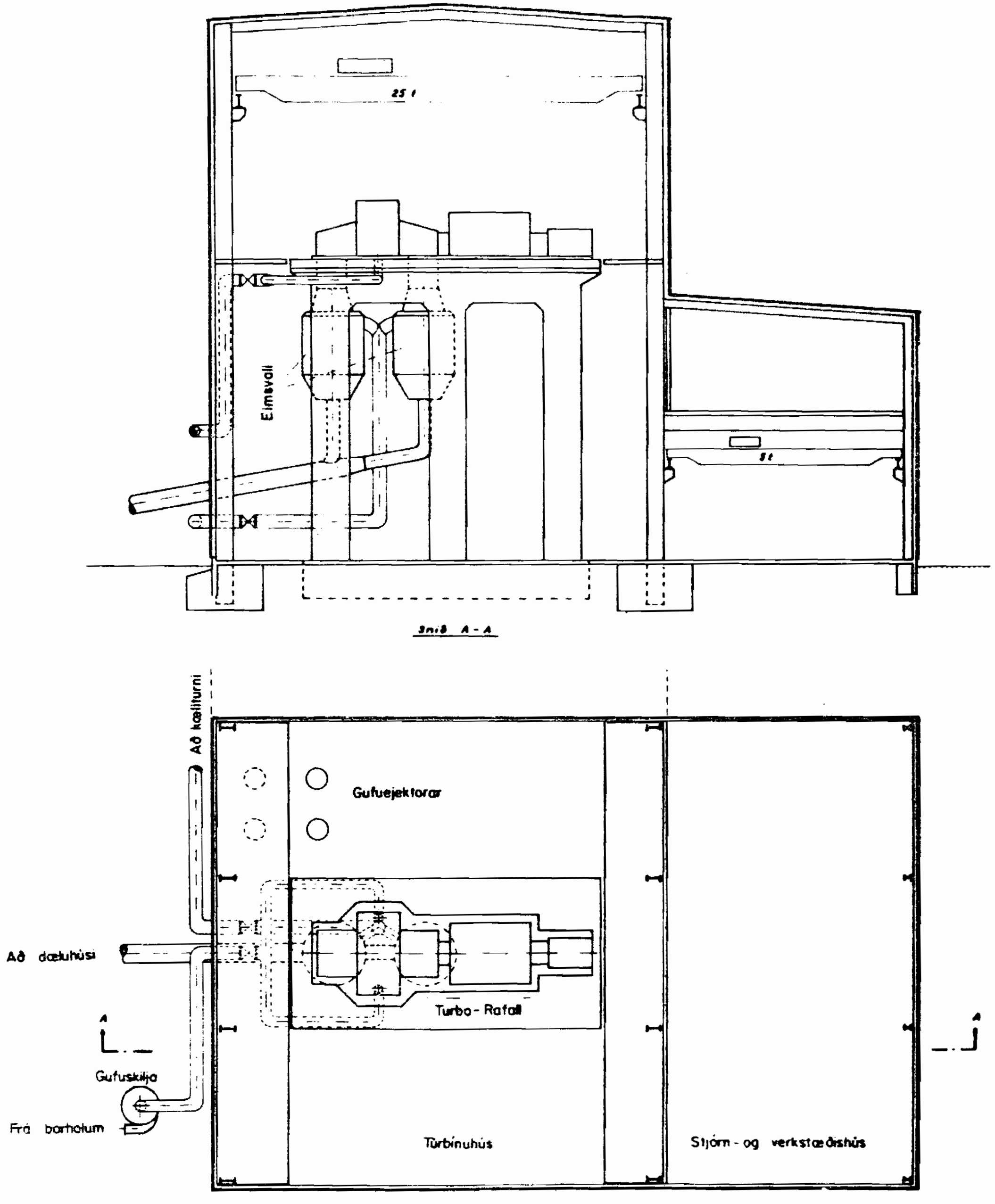
Orkustofnun
Gufuaflstöð við Kröflu
Gufu- og aflkennilínur

Dagb'ók nr.
TEIKNING NR.
K - 2 - 11
Verk nr. blað af


Að gufuejektorum
25 t
5 t
Snið A-A
Snið B-B
Að kæliturni
Dæluhús
Frá eimsvala
Yfirfallskurður
Gufuejektorar
Frá kæliturni
Eimsvali
Að dæluhúsi
Turbo-rafall
Gufuskilja
Frá borholum
Túrbínuhús
Stjórn- og verkstæðishús
VERKFRÆÐISTOFA
GUÐMUNDAR & KRISTJÁNS
28 - 43

Mynd 15





Mynd 16

VERKFRÆÐISTOFA
GUÐMUNDAR & KRISTJÁNS

Orkustofnun Jarðgufuaflstöð
8 MW - Undirliggjandi eimsv
Grunnmynd og snið

1 100

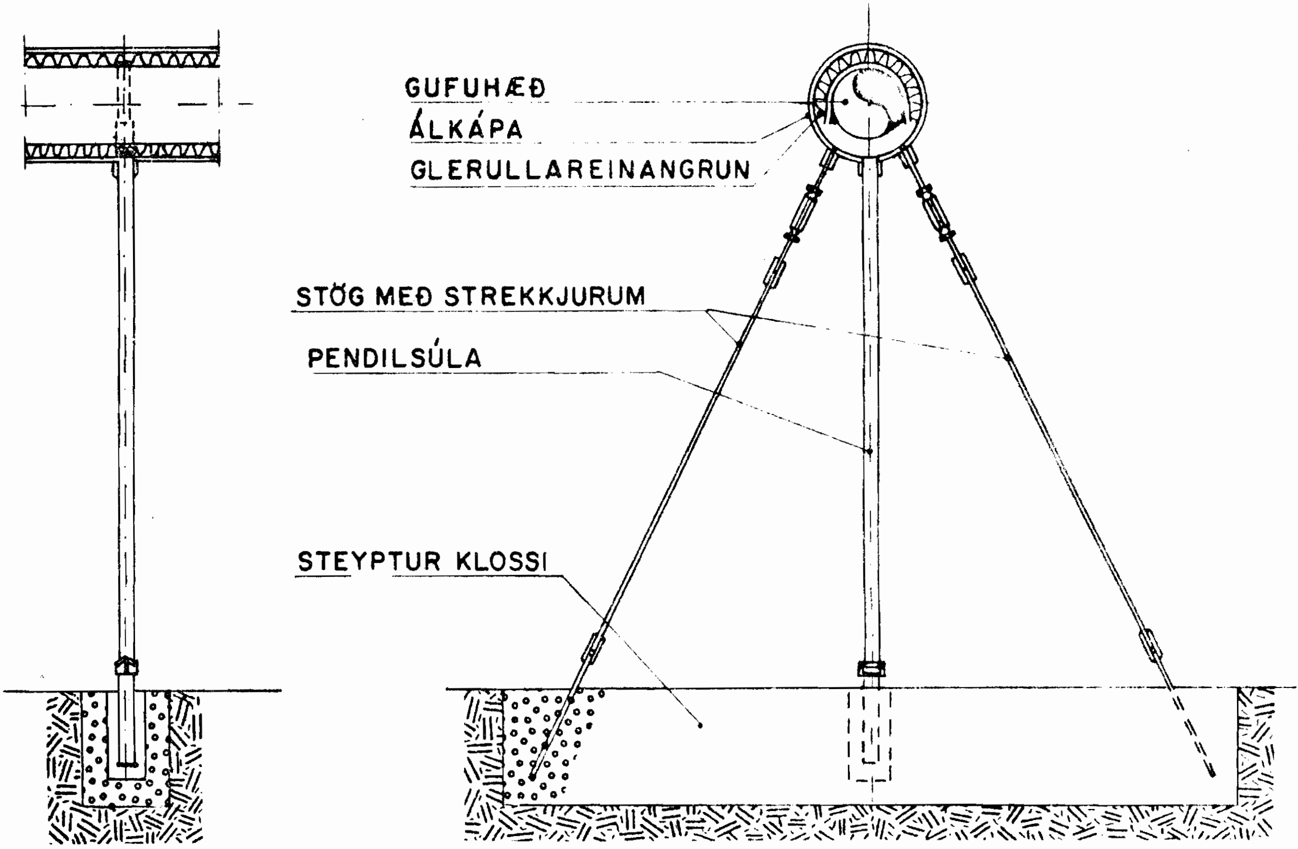
28 - 44

ORKUSTOFNUN

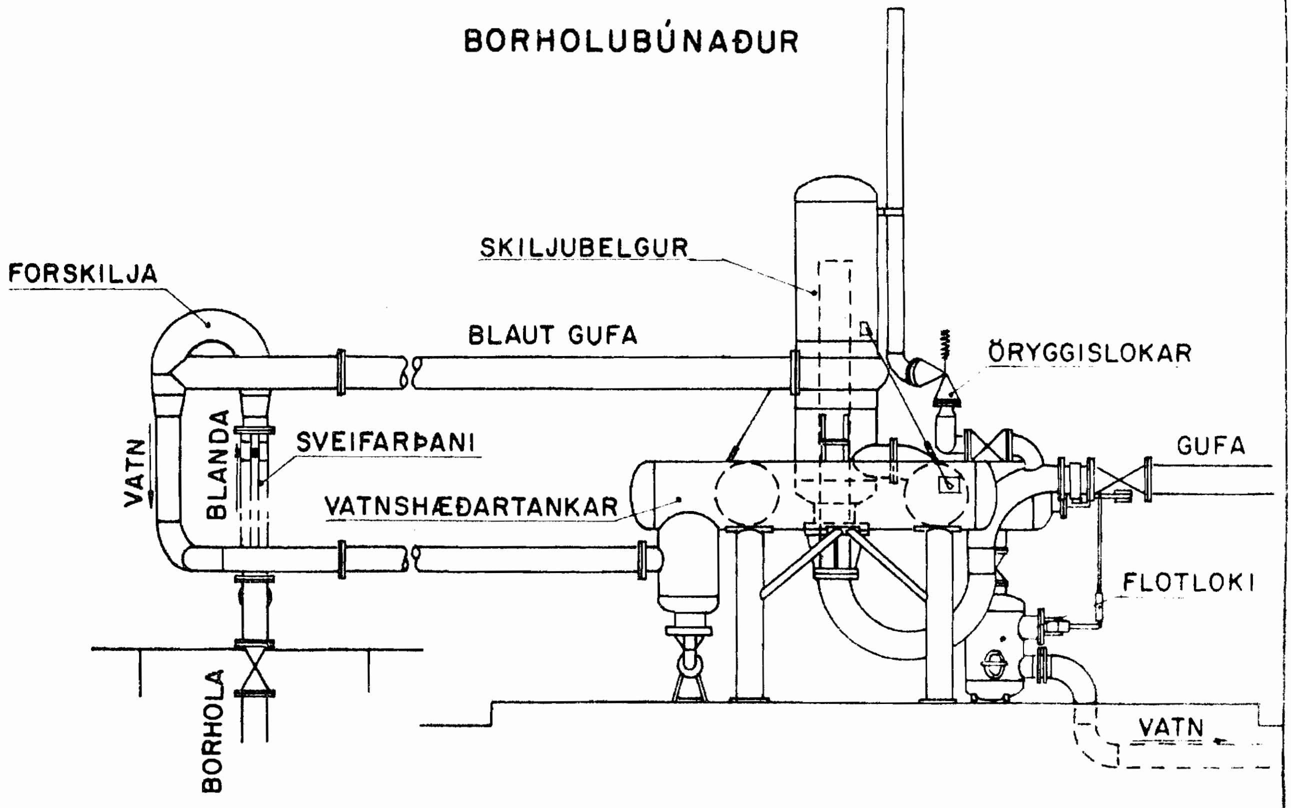
2.3.'72 K.R./EK.
Tnr. 301
J-ým.
Fnr. 10434

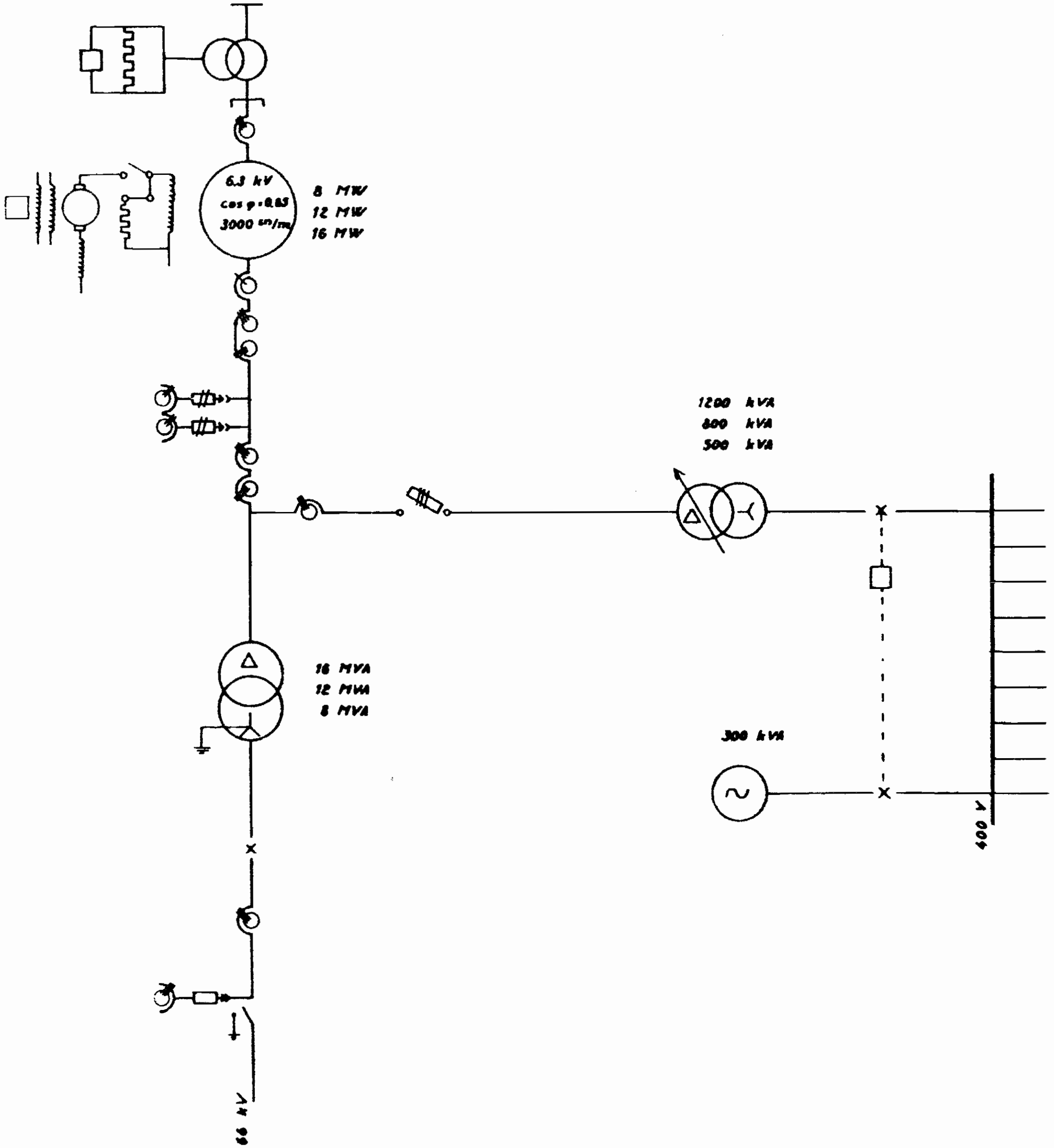
Mynd 17

PENDILSÚLA



BORHOLUBÚNAÐUR





Mynd 18

Fl.	Heiti	Nr.	Teikn. nr.	Efni	Afh.

Breyting

Dags.	Leiðrétting	Dags.	Leiðrétting

VERKFRÆÐISTOFA
GUÐMUNDAR & KRISTJÁNS
Laufásvegi 19 Sími 14425

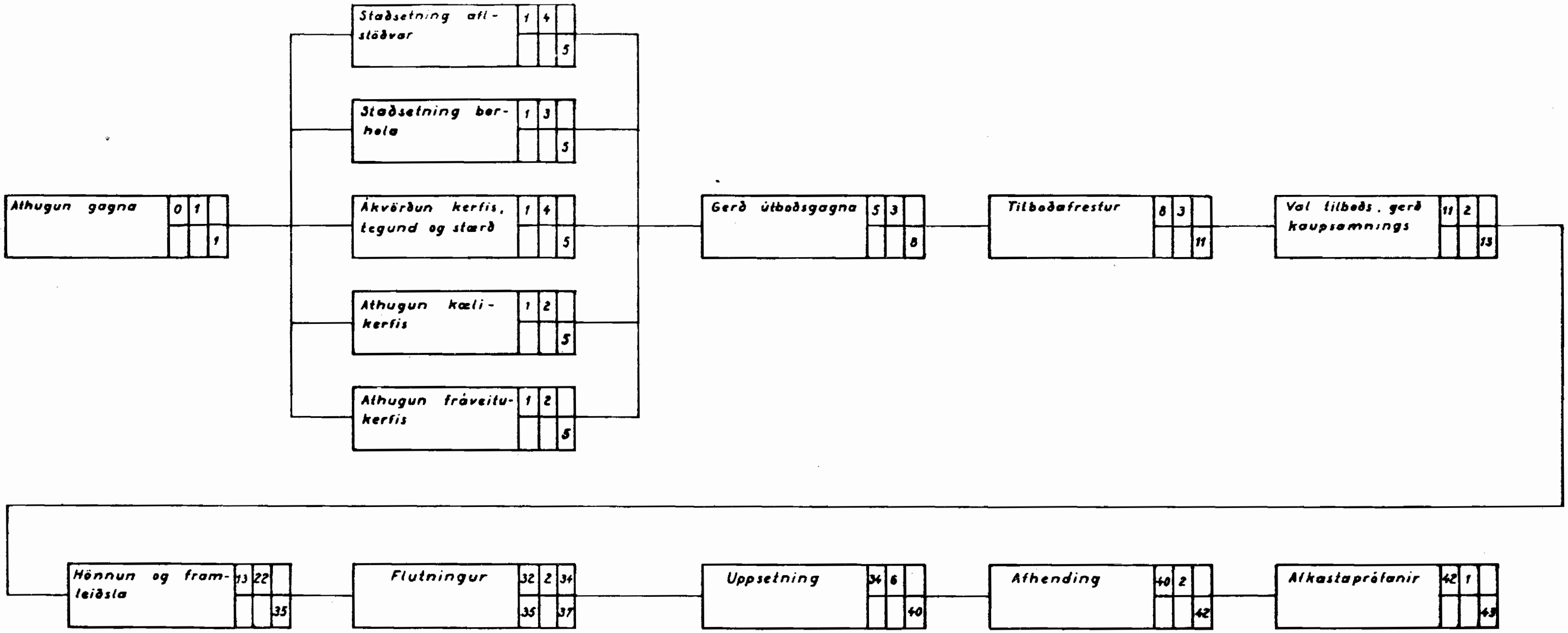
Mælikv.
Verkf.
Teikn.
Yfirf.
Samþ.

Orkustofnun
Jarðgufuaflstöð

Einlinumynd rafkerfis

Dagbók nr.
TEIKNING NR.
2G - 1 - 99

Verk nr. blað af



Skýringar :

Verkþáttur	Byrjað snemma	Varir	Endað snemma
	Byrjað seint		Endað seint

(Tími í mánuðum)

Mynd 19

Fj.	Heiti	Nt. ar	Teikn. nr	Efni	Athe.

Breyting

Dags	Leiðrétting	Dags	Leiðrétting

VERKFRÆÐISTOFA
GUÐMUNDAR & KRISTJÁNS
Laufásvegi 19
Sími 14425

Mkv. ⁄
Verkið 8. 71 JM
Teikn.
Yfirf.
Samþ.

Orkustofnun - Jarðgufuaflstöð

Tímaáætlun Turbo - Rafals

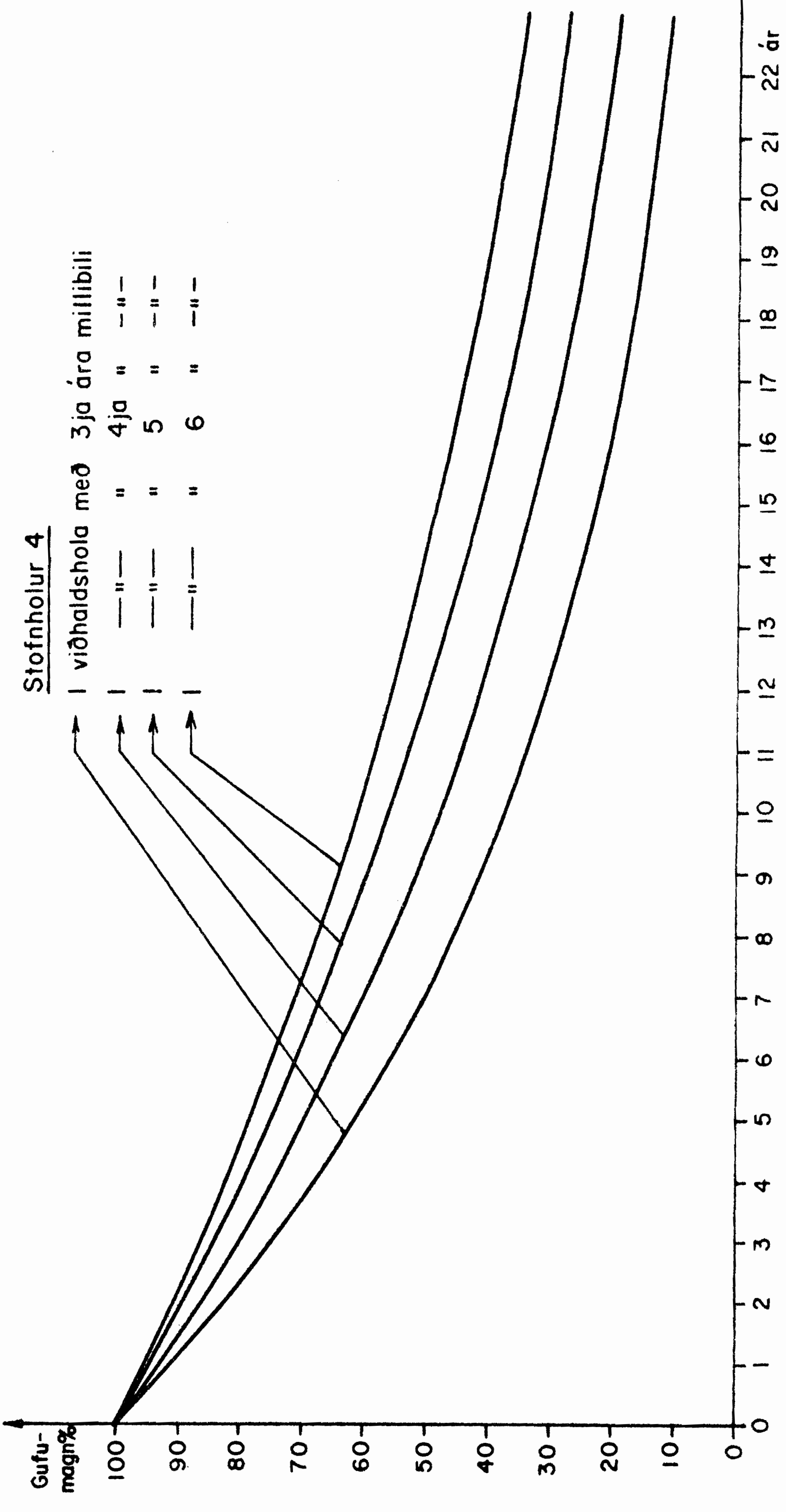
Dagbók nr
TEIKNING NR.
2G - 1 - 83
Verk nr
blað af

ORKUSTOFNUN
Jarðhitadeild

18.10.1971 KR/Gyða
Tnr. 292
J-Ým
Fnr. 10259

Rýrnun gufumagns úr borholu, með tímanum

Mynd 20



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Raforkukostnaður, undir / yfirliggjandi eimsvali

02.05.72 KR/P
Tnr. 329
J- Ým
Fnr. 10539

Mynd 21